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Long-term Ecological Behavior of Abandoned Uranium Mill Tailings

1. Synoptic Survey and Identification of Invading Biota

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LONG-TERM ECOLOGICAL BEHAVIOUR OF ABANDONED URANIUM MILL TAILINGS

1. SYNOPTIC SURVEY AND IDENTIFICATION OF INVADING BIOTA

by

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Toronto, Ontario

for

Environment Canada
Atomic Energy Control Board
Energy, Mines & Resources Canada

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Ottawa (Ontario)
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et demander

Comportement à long terme dans l'environnement
des stériles abandonnés des usines d'uranium

1. Étude synoptique et identification des biotes envahissants

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ABSTRACT

Inactive uranium mill tailings were surveyed in the Province of Ontario to describe their surface characteristics, identify naturally invading biota, and determine essential chemical and physical parameters associated with the tailings.

Inactive tailings sites can have wet areas, tailings completely covered with water, and dry areas. In the wet areas of most sites, wetland vegetation stands were found which were dominated by species of cattails (Typhaceae), along with some species of rushes (Juncaceae) and sedges (Cyperceae). Dry areas of the tailings exhibited a variety of surface features which are often a reflection of different amelioration efforts. Most of the indigenous species of vascular plants identified on dry areas of the tailings occurred only sporadically. Invading plants found on most sites were the tree species, trembling aspen (*Populus tremuloides*) and paper birch (*Betula papyrifera*).

Elemental concentration and some physical characteristics of the tailings collected from a depth of 0-20 cm were determined. The concentrations of calcium and uranium were found to have extremely large variations and cannot be considered typical for the tailings material of a site or an area (Bancroft and/or Elliot Lake). Concentrations of aluminum, copper, cobalt, magnesium, manganese and nickel in the tailings were less varied. In all tailings materials from the Bancroft area, concentration ranges of the above elements were similar to those of soils collected from both areas and to the values quoted in literature. The elements sodium and lead are possibly enriched in the tailings of the Bancroft area compared to mineral soils from the same area, and to soils in general. For the tailings in the Elliot Lake area, aluminum, chlorine, magnesium and nickel were determined in concentration ranges typical of soils, but manganese and sodium were depleted in the surface of those tailings. Lead concentrations in the tailings were elevated in this area. Thus, considering concentrations of selected elements in tailings, differences between the mining areas are evident. A comparison of pH, electrical conductivity, loss-on-ignition and moisture loss of tailings with that of soils, suggests that tailings differ drastically in these characteristics. These results are important with respect to natural rehabilitation of inactive or abandoned uranium mill tailings.

Uptake of heavy metals and radionuclides was evaluated in trees found in the dry areas and in cattails (*Typha latifolia*) in the wetland areas. In trees, the metals and radionuclides were distributed throughout all organs whereas in the cattails, a large fraction was retained in the roots. Concentration factors (plant/tailings concentrations) were found to be generally below unity, with some exceptions for radium-226 in the cattails.

Water bodies on tailings and surface water leaving the tailings, before and after treatment, were characterized in this survey. The surface waters on the tailings and seepages were usually acidic; however, the pH was not lower than that of most waters leaving natural acidic environments (bogs or muskegs). The treatment of the effluent water was found to reduce production of biomass as estimated by determination of chlorophyll α. Radionuclide and metal concentrations in waters associated with tailings were found to have extremely large variations. Detailed work is required to determine the factors controlling the physical and chemical characteristics of surface waters on tailings.

Aquatic bryophytes have invaded some water bodies on the tailings, and acid tolerant algae were evident in most of the water associated with the tailings. The promotion of growth of these biota together with the wetland communities on the tailings beaches may provide some means of natural amelioration for the wet areas of the inactive tailings sites in the long-term. Some inactive tailings sites, described in this survey, were completely covered with water and wetland vegetation. The interactions of these biota with the tailings could be investigated on these sites.

Ecological processes occurring on inactive uranium mill tailings which were identified in this survey are essential in evaluating the long-term fate of these waste sites.

RÉSUMÉ

Les stériles inactifs des usines d'uranium ont fait l'objet d'une étude dans la province d'Ontario, dans le but de déterminer leurs caractéristiques de surface, d'identifier les espèces végétales envahissantes et de trouver les paramètres physico-chimiques des dépôts de stériles.

Les dépôts inactifs peuvent être situés dans un endroit sec ou complètement ou en partie recouvert d'eau. Dans la plupart des sites recouverts d'eau, on a trouvé des peuplements de plantes marécageuses dominés par des quenouilles (typhacées), certains joncs (joncacées) et des carex (cypéracées). Les zones sèches des dépôts possédaient diverses caractéristiques superficielles portant souvent la trace de tentatives de remise en état. La plupart des espèces vasculaires indigènes identifiées ne s'y trouvaient qu'à l'état disséminé. Les espèces envahissantes trouvées dans la plupart des endroits secs étaient les suivantes: le Peuplier faux-tremble (*Populus tremuloides*) et le Bouleau à papier (*Betula papyrifera*).

On a déterminé les caractéristiques physico-chimiques des stériles jusqu'à une profondeur de 20 cm. Les concentrations de calcium et d'uranium variaient énormément et ne pouvaient pas être considérées comme typiques des stériles d'une localité ou d'une région (Bancroft ou Elliot Lake). Les concentrations d'aluminium, de cuivre, de cobalt, de magnésium, de manganèse et de nickel variaient moins. Dans tous les stériles de la région de Bancroft, les différences de concentration de ces éléments étaient semblables à celles qu'on trouve dans les sols des deux régions et aux valeurs communiquées dans les publications; le sodium et le plomb sont probablement présents en concentration enrichie dans les stériles, comparativement aux sols minéraux de cette région et aux sols en général. Les stériles de la région d'Elliot Lake, avaient des teneurs en aluminium, chlore, magnésium et nickel approximativement égales à celles des sols environnants; toutefois, le manganèse et le sodium se trouvaient en concentration moindre à la surface des stériles, et la concentration de plomb y était élevée. Ainsi, en analysant certains éléments des stériles, on constate des différences entre les régions minières. Une comparaison du pH, de la conductivité électrique, de la perte au feu et de la perte d'humidité des stériles et des sols révèle la grande différence qui existe au niveau de ces paramètres. Ces résultats sont importants pour la remise en état naturelle des dépôts inactifs ou abandonnés des usines d'uranium.

L'absorption des métaux et des radionucléides par les arbres fait en sorte que ces matières se répartissent dans l'ensemble des organes, tandis que les quenouilles (*Typha latifolia*) retiennent ces matières en grande partie dans leurs racines. Les teneurs (dans les plantes par rapport aux stériles) étaient en général inférieures à l'unité, le radium 226 présentant quelques exceptions chez les quenouilles.

Les eaux recouvrant les dépôts et les effluents des bassins de stériles ont été caractérisés avant et après traitement. Les eaux qui recouvrent les stériles et l'eau d'infiltration étaient généralement acides; toutefois, le pH n'était pas inférieur à celui de la plupart des eaux de milieux naturellement acides (tourbières ou muskegs). On s'est aperçu que le traitement de l'effluent avait réduit la production de la biomasse, déterminée par la chlorophylle a. Les concentrations de radionucléides et de métaux dans les eaux associées aux stériles variaient énormément. Il faudra une étude approfondie pour isoler les facteurs qui déterminent les caractéristiques physico-chimiques des eaux qui recouvrent les stériles.

Des bryophytes aquatiques avaient envahi certaines eaux recouvrant les stériles, et des algues tolérantes aux acides pouvaient s'observer dans la plupart des eaux associées aux stériles. À la longue, le fait de favoriser la croissance de ces espèces ainsi que des communautés lénitiques à la périphérie des bassins de stériles peut procurer des moyens d'améliorer naturellement les sites des dépôts recouverts d'eau. Certains dépôts inactifs, décrits dans la présente étude, étaient complètement recouverts d'eau et de végétation lénitique. Les interactions de ces espèces et des stériles pourraient y être étudiées.

La connaissance de l'évolution des dépôts de stériles inactifs des usines d'uranium dans l'environnement est essentielle à l'évaluation à long terme du devenir de ces dépôts.

FOREWORD

In the Elliot Lake and Bancroft districts of Ontario, uranium mining/milling activities have been continued with varying intensities since the early 1950s. At present, there are over 100 million tonnes of tailings covering several hundred hectares of land in this province alone. The tailings materials contain about 85% of the initial radioactivity and some process reagents, e.g. ammonia, nitrates, sulphates, etc. Therefore, the potential hazards to humans and environment that may be posed by their presence in the ecosystem need to be assessed.

Some of the uranium mill tailings sites have been inactive/abandoned for nearly 20 years and have been subjected to the physical, chemical and biological forces of weathering. However, their potential environmental implications have not been fully evaluated. To study the long-term impacts of those tailings on the environment, a detailed investigation was initiated in 1980. The results of the first phase of the multi-year study are presented in this report. It is hoped that the report will be of value to those working in the area of uranium mill tailings management. The project will eventually provide a data base which could be used in modelling and future forecasting of impacts.

The research work was carried out under contract by Margarete Kalin of the University of Toronto. Funding for the project was jointly provided by the Atomic Energy Control Board, Energy, Mines & Resources Canada and Environment Canada.

Nuclear Programs Division
Environmental Protection Service
Environment Canada

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1 INTRODUCTION

1.1 General

In conventional mining and milling of uranium, the large amount of residual material produced after the extraction of uranium from the ore is known as uranium mill tailings. The demand for energy results in an increasing demand for uranium to fuel the nuclear reactors. Expansion of present uranium mining operations, development of new mines, and exploration for new uranium deposits are thus being vigorously pursued. It is estimated that the uranium production in Canada will double over the next 10 years. As a result of the future expansion of uranium production, mill tailings are expected to reach a volume of several hundred million tonnes by the end of this century.

Tailings are deposited most frequently in natural depressions confined by engineered dams. Safe management of the vast amount of waste material is an integral part of the entire mining operation. Immediate detrimental effects of the tailings on the environment are curtailed by appropriate treatments as part of the operations of the mine. At the end of the mining activities, appropriate steps must be taken to close out or decommission the tailings sites. Clear guidelines for the ultimate disposal of the tailings have yet to be developed.

The ultimate objective in decommissioning tailings impoundments is to create a "walk away" situation which requires no maintenance. The tailings management scheme used in the future should leave the waste sites in a state that ensures minimal detrimental effects on the environment. The objective of decommissioning the waste sites requires a complete understanding of all the significant processes which take place during aging of the impoundments.

The waste materials are subject to biological, chemical and physical processes. The interaction of these processes with the tailings and the immediate surroundings are instrumental in determining the long-term fate of the tailings sites. It follows that observations made on tailings which have been exposed to the environment for some length of time are useful in predicting the future of the tailings sites.

In the provinces of Ontario and Saskatchewan (Canada), some tailings impoundments were left abandoned since the decline of uranium production in the late 1950s. The present investigation focuses on abandoned uranium mill tailings sites in Ontario. Fundamental to the investigation is a detailed description of the 15- to 23- year old sites. The description and determination of ecological aspects of the tailings sites which indicate important processes are emphasized in the study. A further aim is to assemble a solid information data base about inactive uranium mill tailings. From this information, a direction can be derived for further investigations which facilitate reliable predictions on the long-term fate of these waste depositories.

1.2 Specific Objectives of the Investigation

In 1980-81, 15 abandoned uranium mill tailings sites in the Bancroft and Elliot Lake (Ontario) area were surveyed. Three of the tailings surveyed in the Bancroft area were typical abandoned sites; the remainder of the sites in Bancroft and all the sites in Elliot Lake are actively managed by the operating uranium mining companies. The latter sites, however, have experienced years of weathering and provide a useful data base to the study.

Indigenous vegetation growing on the tailings was identified. Selected physical and chemical characteristics of the tailings surfaces and the water bodies on the tailings were determined. Uptake of radionuclides and heavy metals in indigenous vegetation growing on tailings was assessed. Processes which appear of significance in the long-term fate of the tailings were delineated.

2 MATERIALS AND METHODS

2.1 Location and Physical Dimensions of the Tailings Sites

The Province of Ontario has two uranium mining districts located in the central and southern part of the province (Map 1). The locations of the inactive tailings sites surveyed in the Elliot Lake area are shown in Map 2, and in the Bancroft area in Map 3. These locations represent all major inactive uranium mill tailings sites in the Province of Ontario. The physical dimensions and historic data of the impoundments are summarized in Table 1. Important characteristics of the sites are: the tonnage of the tailings deposited; the exposed dry surface area; the time since active impoundment of tailings has ceased on the sites; and the years since surface amendment application. The nature of the original landform which existed before the tailings were deposited in these locations is also shown.

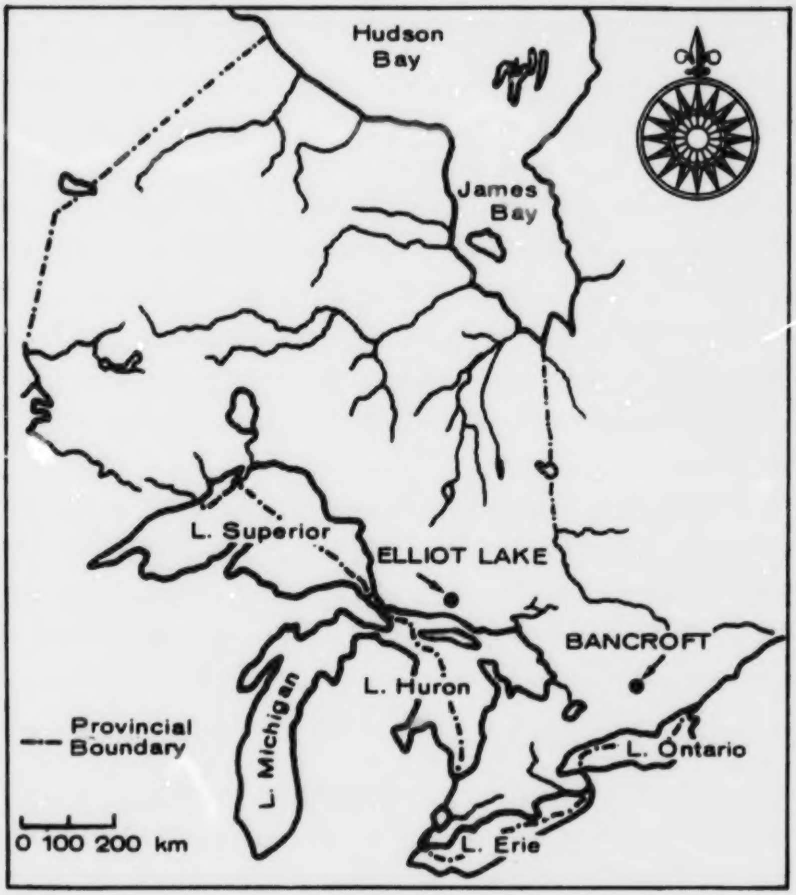
In both mining areas, uranium was extracted by acid leaching; and the tailings slurries were neutralized before they were discharged into the tailings ponds. The ore from the Elliot Lake area is pyritic, thereby rendering the tailings potentially acidic. The Elliot Lake tailings can be differentiated from those of the Bancroft area which are less acidic due to a lower pyrite content of the ore.

2.2 Collection of Materials

During the entire survey, all of the materials were collected and sampled from the Bancroft area first, followed immediately by collections in the Elliot Lake area. Field trips to each area averaged 5 to 8 days. Materials collected included plants, tailings and water samples. For the water samples, the timing of collection was particularly important.

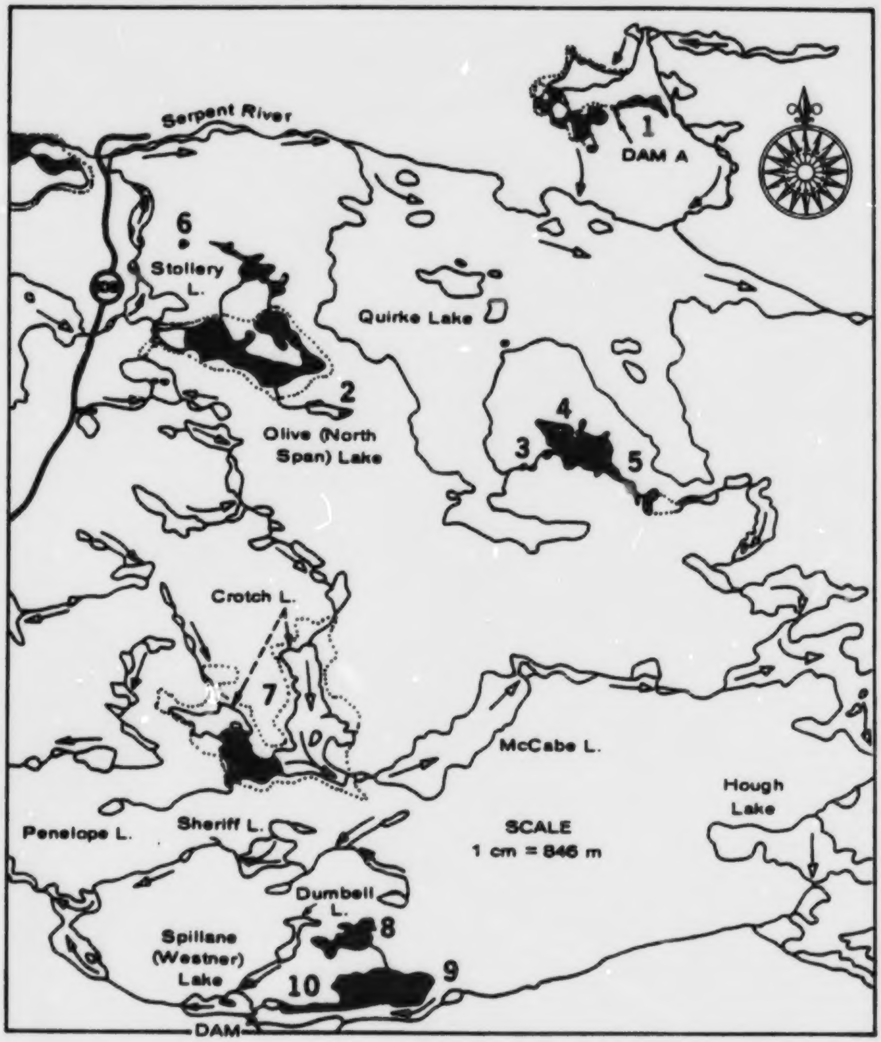
2.2.1 Preparation of the Maps. For each tailings site, outlines were drawn from aerial photographs; enlargements of standard size photographs were used where required. The aerials were from the 1969 and 1973 series. All investigated tailings sites were inactive at the time of the aerial flights. The surface area of the sites was determined by planimetry based on the original aerials.

Surface characteristics of the tailings ponds were derived by several steps. Initially, random transects were walked on all sites. A familiarity with the site characteristics was thus gained by the investigator for each location. Most tailings ponds


Hudson Bay
James Bay
L. Superior
ELLIOT LAKE
BANCROFT
L. Huron
L. Michigan
L. Ontario
L. Erie
Provincial Boundary
0 100 200 km

MAP 1 LOCATION OF ELLIOT LAKE AND BANCROFT, ONTARIO (from Dore and McNeill, 1980)

had relatively uniform sections where random transects were appropriate to assess the cover. The interface of the tailings basin with the surrounding forests exhibited large variations in character. Therefore, all borders of the tailings sites were surveyed in addition to the random transects in the open areas.


Serpent River
1
DAM A
6
Stollery L.
Quirke Lake
2
Olive (North Span) Lake
4
3
5
Crotch L.
7
McCabe L.
Hough Lake
Penelope L.
Sheriff L.
SCALE
1 cm = 846 m
Dumbell L.
8
Spillane (Westner) Lake
10
9
DAM

MAP 2 OVERVIEW OF THE ELLIOT LAKE STUDY AREA
(from Environmental Assessment Board, 1979; modified)

LEGEND

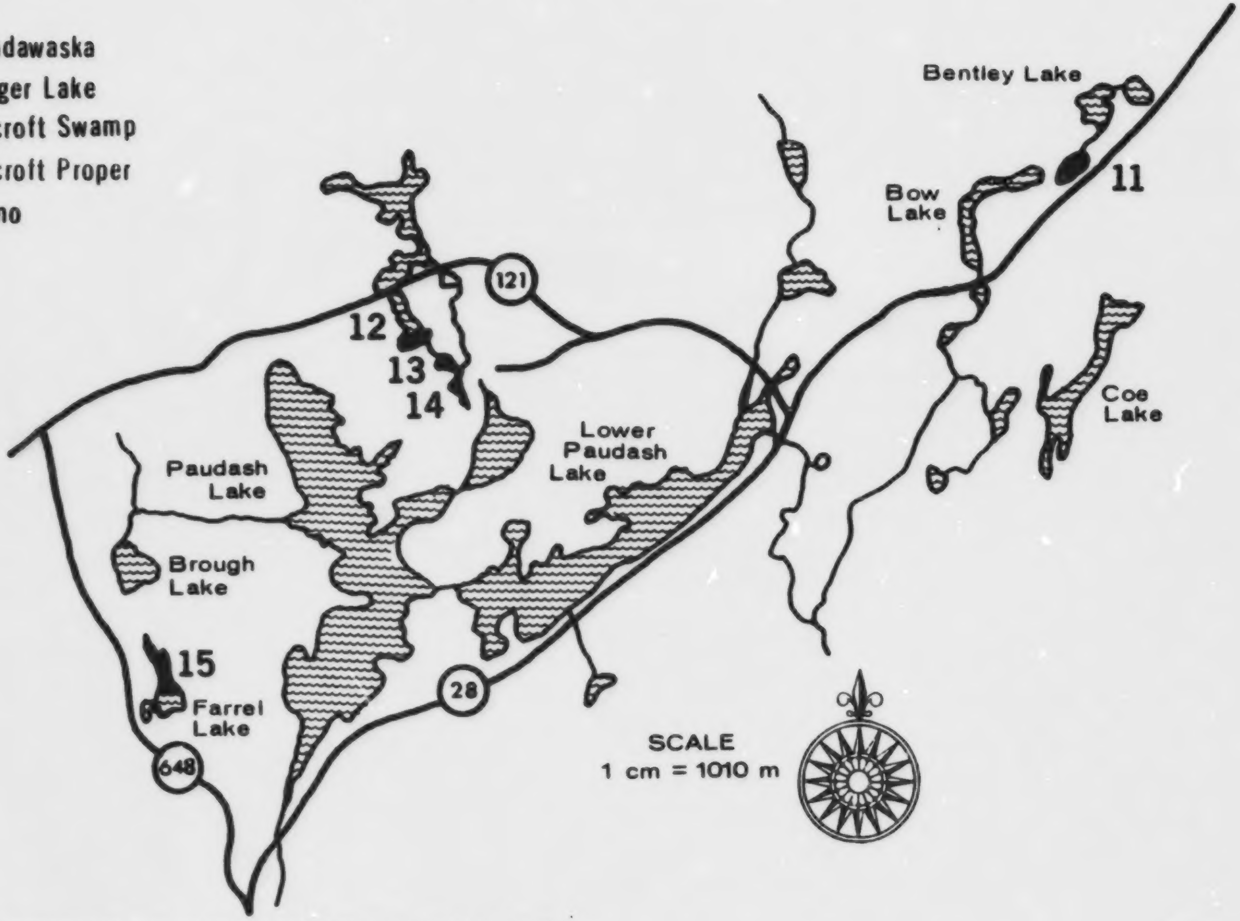
1. Panel Dam A
2. Olive Lake
3. Stanrock Dam G
4. Stanrock Main
5. Stanrock Dam A
6. Lower Williams
7. Crotch Lake
8. Lacnor
9. Nordic Main
10. Nordic West Arm

NOTE: The names of the tailings sites used in Maps 2 and 3 are used throughout this report.

Scale: 1 cm = 1010 m

LEGEND

11. Madawaska
12. Auger Lake
13. Bicroft Swamp
14. Bicroft Proper
15. Dyno


Bentley Lake
Bow Lake
11
Coe Lake
121
12
13
14
Lower Paudash Lake
Paudash Lake
Brough Lake
15
Farrel Lake
28
648
SCALE
1 cm = 1010 m

MAP 3 OVERVIEW OF THE BANCROFT STUDY AREA
(from Ontario Water Resources Commission, 1971; modified)

TABLE I DIMENSIONS AND HISTORIC DATA OF ABANDONED URANIUM MILL TAILINGS SITES IN ONTARIO

Location	Amount (t x 10^6)	Dry Surface Area (ha)	Years Since Impoundment Ceased (as of 1980)	Years Since Amendment (as of 1980)	Landform Before Tailings Deposition
Bancroft Area:					
Dyno	0.57*	2.7	20	-	Lake
Bicroft Proper	0.35	3.8	23	-	Swamp
Auger	2.00	1.8	17	-	Lake
Bicroft Swamp	?	2.2	?	-	Swamp
Madawaska No. 2	1.7	16.0	16	2	Swamp
Elliot Lake Area:					
Nordic Main	9.00	85.0	12	10 - 5	Valley
West Arm	3.00	16.0	19	5 - 2	Swamp
Lacnor	2.70	24.0	20	1 or 2	Swamp
Olive	0.45	5.0	21	3	Lake
Panel Dam A	0.24*	1.3	19	..	Lake
Crotch	7.50	53.0	16 or 20	10	Lake
Williams	0.10	2.0	21	4	Pond with swamp
Stanrock Main	5.50	63.0	16	2	Valley
Dam A	0.45	6.0	16	-	Creek
Dam G	0.082	2.0	16	-	Creek

Summary	Million tonnes	Hectares of Dry Surface Area	Million tonnes/ha
Bancroft	4.6	26.5	0.17
Elliot Lake	29.0	257.3	0.11

* estimate - calculations are given in Appendix I.

information obtained from: Rio Algom Ltd., Denison Mines Ltd., Madawaska Mines Ltd., and Mr. J.C. Edward, pers. comm.

also from: Griffith (1967), Ontario Water Resources Commission (1971)

The spatial distributions of the mapped characteristics within the sites were obtained either by counting steps or by using a measuring tape. Preliminary maps were drawn which were confirmed on subsequent field trips.

2.2.2 **Collection of Vascular Plants.** Vascular plants were collected from all sites in Elliot Lake and Bancroft throughout the season. The specimens were pressed, identified and deposited at the University of Toronto herbarium. The plant collection from the tailings sites of Auger Lake, Bicroft Proper and Madawaska No. 2 were more complete than for all of the Elliot Lake sites. These three sites have been studied in detail by Stokes and Kalin (1978), and by Caza (1980).

2.2.3 **Collection of Tailings.** The locations for sampling the tailings materials were determined based on the type of surface cover. Bare tailings (i.e. tailings devoid of vegetation) and tailings associated with vegetation were sampled at the surface (0-5 cm) and in the root region (20-25 cm). The samples were secured as grab samples collected with a hand trowel after a pit was excavated with a spade.

2.2.4 **Collection of Vegetation for Analysis.** Cattails and trees were collected for uptake studies of elements. The sampling procedure is described later. After excavating the cattails, the plants were immediately separated into leaves, stems, seeds, roots and rhizomes, with the latter two being transported with the growth substrate (tailings or soil) intact. The collected materials were transported in coolers and were refrigerated upon arrival in the laboratory.

Around the trees, plant association and type of surface cover (e.g. moss, litter or bare surface) was described in the immediate quadrat (1 m^2) of the specimen which was collected for analysis. The height and width of the trees were measured. Each tree was then placed on a cotton sheet to ensure that the tailings directly around the roots were sampled and were not mixed with other materials. The soil and the tailings were then removed from the roots of the trees and root morphology was recorded photographically. The roots were subsequently removed in the field.

2.2.5 **Collection of Water Samples.** Water associated with tailings was sampled during three seasons of 1980. The first sampling was taken in March before the run-off; the next shortly thereafter in April and May, just after the melting of the ice; and the third towards the end of summer in the month of September. In March, samples were collected through a hole in the ice drilled by a hand auger. Ice chips were removed from the hole and a water sampler on a stick was submerged to a depth of 1 m. Dissolved oxygen, pH and electrical conductivity were determined in the field.

In shallow water bodies, the samples were collected from the surface of the water. In the deeper water (depth >1 m), pH and oxygen profiles were obtained. The water was collected in most locations at a depth of 1 to 1.5 m. All samples in deep locations were secured with a "student" water sampler. Seepages from tailings and creeks running on the tailings were collected directly into the sampling bottles.

At each sampling location, three litres of water were collected. One litre was filtered through 0.45 μm filter paper. The filtrate was acidified with concentrated nitric acid and retained for heavy metal and radionuclide analyses. The filter papers were kept in order to determine suspended matter. The second litre was also filtered through 0.45 μm filters, but the filters were treated with saturated magnesium carbonate solution and retained for chlorophyll analysis. The filters were then stored in plastic petri dishes, wrapped in aluminum foil, and stored immediately on dry ice or in freezers. In the laboratory, the filters were frozen at a temperature of -50°C and processed within 2-3 weeks after collection. The filtrate of the chlorophyll was retained for determination of dissolved matter. The third litre was acidified without filtration in order to obtain total matter. Filtration was carried out within a 6 to 8 hour period after collection of the water.

2.3 Sample Preparation and Determination

Three types of samples were collected for analysis - vegetation, tailings and water. The procedures and methods used to determine physical characteristics for each material preparation are given below. Details of these procedures are given in Appendix I.

2.3.1 Vegetation. Samples of *Typha latifolia*, *Populus tremuloides* and *Betula papyrifera* were separated into stems, roots, leaves, seeds and rhizomes where appropriate. The plant parts were washed under tap water with pressure; if necessary, the parts were scrubbed with a brush to ensure complete removal of particulates. The washing was followed by several rinses in distilled water with detergent (Palmolive brand) and three rinses with pure distilled water. The cleanliness of all materials was confirmed under a microscope.

The samples were cut into small pieces and homogenized in a commercial Waring blender. Certain plant parts required the addition of distilled water during blending. The samples were dried at 70°C in a drying oven (Dispatch Model LDB 1-69) to obtain a dry weight of approximately 2 g of plant material. All the remaining materials were frozen at -50°C.

2.3.2 Preparation of Tailings Samples. The entire grab sample was removed from the bag and emptied onto a sieve. The samples were described for texture and colour. Stones and other large objects were removed and the material was homogenized in a mortar; a sub-sample was then removed for analysis.

Determinations of moisture content and of loss-on-ignition (LOI) were made for most samples using approximately 5 g of homogenized material. When the sample had reached a dry point, approximately 1 g of the material was removed for atomic absorption analysis; 0.5 g was removed for neutron activation analysis. The remainder of the dried material was re-weighed and ignited at 450°C for 4 hours in a muffle furnace. The ignited samples were then re-weighed after cooling to determine the LOI.

2.3.3 Conductivity and pH Determinations of Tailings and Soils. A pH measurement of the tailings in the field was carried out on wet locations by immersing the pH electrode in the excavated pit. Most sampling locations were relatively close to the water table where the thixotropic tailings immediately formed a slurry in which the determinations could be made.

In the laboratory, conductivity and pH of the tailings and the soils were determined on 20 g (fresh weight) of material mixed in a test tube with 20 mL of distilled water. The slurry was allowed to sit for 30 minutes after which it was mixed with a test tube vibrator and the pH and conductivity determined. Both measurements were repeated after the slurry was allowed to stand for 24 hours at room temperature.

On tailings which were dried, pH and conductivities were again determined for the samples obtained with vegetation. Preparation of the tailings slurry was identical to the fresh tailings samples. All pH measurements were made with an I.L. Portomatic pH meter Model No. 175, using a Canlab Gel. combination electrode. Conductivity was determined with a conductivity meter HACH Model No. 17250. The conductivity of the water and tailings is reported as electrical conductivity in μmhos/cm throughout this report.

2.3.4 Determination of Water Characteristics. The water samples filtered and acidified in the field were evaporated to determine dissolved matter and total matter. For the spring samples, approximately 1 L portions were evaporated, whereas for the autumn samples only 100 mL portions were evaporated. The determinations of total and dissolved matter were performed according to ASTM (1979) Standard Method D-1888-78. The volatile fraction of the total matter was determined only for the spring samples.

Filter papers with suspended matter were dried in petri dishes with silica gel for 3 days at 75°C. The weights of clean filter papers were determined for 10 Gelman filters (GN-6) using an analytical balance (Sartorius Model No. 2474) with a precision of ±0.01 mg. Chlorophyll *a* was determined in the spring and autumn samples following the ASTM (1979) Standard Method No. D-3731.

2.3.5 Wet Oxidation of Vegetation and Tailings. The dried and homogenized plant parts were cold digested for 24 hours with 50% nitric acid. Concentrated nitric acid was added for a second 24-hour period. The samples were heated slowly and brought to a boil. Some parts of the plants are easily expelled from the boiling tubes. Long glass rods inserted into the tubes prevented the samples from boiling over. Upon cessation of brown fumes, additional concentrated nitric acid was added. The samples were boiled a further 24 to 48 hours until white fumes ceased. After cooling, the digests were filtered through S & S 589 Black Ribbon filters and brought to 25 or 50 mL in volumetric flasks with distilled water. Acid blanks were prepared with each batch of oxidations.

Tailings and soils were cold digested with concentrated nitric acid for 24 hours after which they were heated for another 24-48 hours until brown fumes ceased. Concentrated perchloric acid was added to cooled samples, and boiling continued for 24-48 hours until white fumes ceased. The samples were then allowed to cool and filtered as described for vegetation.

For all digestion procedures (vegetation, tailings and soils) the boiling temperatures were between 110° and 120°C. All digests thus prepared were stored in snap-top PVC vials which were washed in 4% HCl and rinsed seven times with distilled water.

2.4 Analytical Methods

To reduce sample variation to a minimum, the dried homogenized material was sub-sampled for wet oxidation and for neutron activation analysis as described in Section 2.5.2. The analyses of the metals preceded the radionuclide analysis to secure a maximum available volume of the digest for the radiochemical procedures.

Standard NBS (National Bureau of Standards) plant material, EPA (Environmental Protection Agency) water and "Round Robin" lake sediment from the CCIW (Canada Centre for Inland Waters) were used to check digestion and analytical procedures. The results to evaluate the efficiency of the digestion and analytical procedures are presented in Appendix I.

2.4.1 Atomic Absorption. The metals copper, cobalt, nickel and lead were determined with a Varian A.A. No. 6 flame atomic absorption spectrophotometer, utilizing hydrogen continuum background correction. The detection limits and errors in the different materials analyzed for these metals are given in Appendix I.

2.4.2 Neutron Activation. The neutron activation capsules containing dry tailings material were approximately half-full. The capsules containing vegetation material were completely packed. One millilitre of liquid samples was pipetted into the capsules which were heat sealed prior to irradiation. All capsules were handled with gloves to prevent contamination.

The capsules filled as described were irradiated individually at the SLOWPOKE reactor (Safe Low Power Critical Experiment) at the University of Toronto. The irradiation scheme shown in Appendix I was determined experimentally to accommodate multi-elemental analysis in all matrices (water, tailings and vegetation). Some elements were not abundant enough to be determined in absolute concentrations; however, values smaller than or equal to a given concentration are reported for these instances.

An assessment of concentrations, or upper limits of concentrations, for aluminum, barium, bromine, calcium, chlorine, cobalt, dysprosium, iodine, magnesium, manganese, uranium, sodium, strontium, and vanadium were made. Errors and detection limits for the neutron activation are given in Appendix I.

2.4.3 Radiochemistry. Water samples were passed through a cation exchange resin [Dowex-50W-X8 (200-400)] as they were prepared in the field. The vegetation digests were evaporated to a small volume and subsequently diluted with distilled water, adjusted to a pH of 1 to 2 and passed through the resin. Tailings and soil samples were contacted with a DTPA solution to extract radium and other cations after which they were centrifuged to separate the insoluble material. The supernatant was acidified and then passed through the ion exchange resin. After passage through the ion exchange resin, radium-226 was eluted from the resin with 12 M HCl. Lead-214, bismuth-214 and bismuth-210 were assayed for beta activity by using a low background gas flow proportional counter within 20 minutes after extraction from the resin. After a minimum of 24 hours from the end of the extraction, samples were recounted since the activity of bismuth-214 and lead-214 had decayed. Radium-226 activity was determined by the application of the standard decay equations. An example of the calculations and further details of the methods are given in Appendix I.

Detection limits and errors are a function of the amount of material provided for the analyses and the activity of the sample. Each determination of radium-226 and lead-210 concentrations is thus reported with an error.

3 RESULTS

3.1 Surface Features of Abandoned Uranium Mill Tailings

A total of 15 tailings sites investigated in this study have been inactive for approximately two decades. In the Bancroft area, one unconfined tailings spill and three tailings deposits contained within the dams were selected for the survey. In the Elliot Lake area, the survey was carried out on three accidental spill areas and seven designated tailings ponds, most of which have been amended in the past years.

In the Bancroft area, the tailings tonnage per hectare of dry surface area is considerably lower than in Elliot Lake (Table 1). Three large sites exist in Elliot Lake (Nordic, Stanrock and Crotch Lake) which hold the bulk of all the inactive tailings material. Two of these large sites are tailings depositions in former valleys and the third site has been formed from a lake. The remaining tailings tonnage in Elliot Lake - about 4 million tonnes - covers 40 ha of land surface. In Bancroft, approximately 4.5 million tonnes of tailings are deposited in natural depressions, all previously associated with some type of water (creeks, swamps or small lakes), which cover 26.5 ha of land.

Essentially, each tailings site investigated in this survey differs from the others in most characteristics (Table 1). Similarities between the sites include the years since active tailings impoundment ceased and the former landform in which the tailings have been deposited.

3.1.1 Description of Characteristics Identified on Tailings Surfaces. Despite the apparent differences between the tailings sites, similarities with respect to surface cover characteristics can be observed. Reoccurring characteristics of the tailings surfaces are given in Table 2.

Eight types of vegetation cover can be distinguished. Revegetated dead or alive refers to an introduced grass cover, the composition of which can vary from site to site and within a tailings area. Moss cover refers to areas of moss cushions on tailings, to mats of moss in revegetated areas, and also to larger areas dominated by moss and other non-vascular plants.

Tree occurrences on the tailings were recorded as tall trees and tree seedlings. Most seedlings had just passed the cotyledon stage and were rarely more than 15 cm high. Tall trees were at least 60 cm high, with most of the trees in this category being 1 to 2 m high.

TABLE 2 REOCCURRING SURFACE FEATURES OF ABANDONED TAILINGS SITES

☐	Bare tailings	⫶	Tree seedlings
▤	Bare tailings with lime or limestone	•	Shrubs
⁘	Revegetated (alive)	●	*Typha* colonies only
▲	Revegetated (dead)	ꝏ	Sedge colonies only
☆	Moss cover	●	Mixed *Typha* and sedge
✱	Trees	≋	Water on tailings

The trees species included mainly trembling aspen, balsam poplar and white birch. Shrubs rarely constituted a significant surface cover on the tailings sites; hence these woody plants were not recorded in the discussed tree categories. Wetland vegetation on the tailings was differentiated into the dominant plant families with stands of Typhaceae and Cyperaceae being distinguished and recorded as pure *Typha*, sedges or mixed stands. No distinction was made for the mapping purposes between Cyperaceae (sedges) and Juncaceae (rushes).

Bare tailings and tailings with lime or limestone are surface characteristics which are self-explanatory. The symbols used on the maps prepared for the tailings sites are indicated in Table 2.

The depth of water bodies on the tailings varied, but only water bodies which appeared permanent were recorded on the maps. The categories defined above are broad; when studied in detail, subtle differences between and within the sites may be discernible. However, the described categories form a reasonably complete inventory of characteristics found on abandoned tailings surfaces.

3.1.2 The Elliot Lake Sites. The locations of the inactive tailings sites surveyed in the Elliot Lake area are shown in Map 2. A detailed description of each individual site is given in the following sections. The sites are grouped by similarities of surface characteristics.

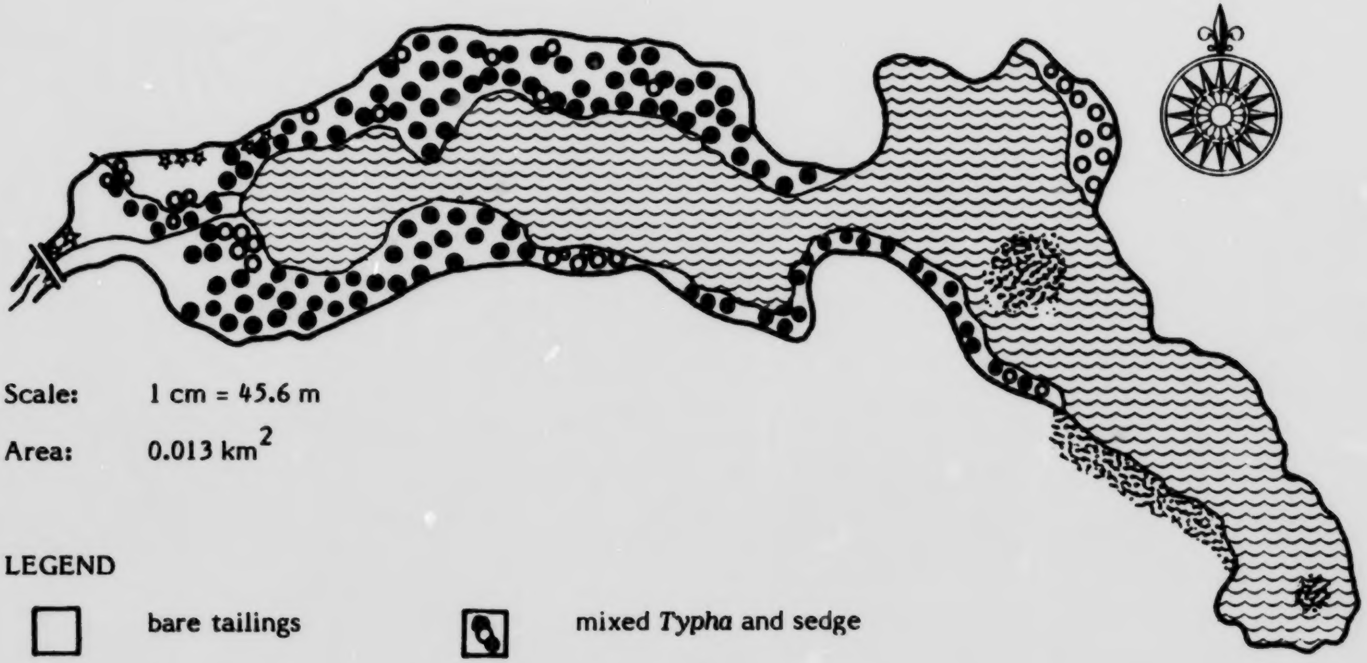
3.1.2.1 Sites with wetland vegetation and bare tailings. Panel Dam A is an inactive section of a presently active tailings pond (Map 4). The tailings are covered with very shallow (20 to 50 cm deep) water. Extensive stands of *Typha* have invaded the tailings leaving only the centre of the pond as open water. There are some pockets of sedges in the eastern section where the shores are rocky and the water drains into a swampy area. Aquatic mosses form small hummocks in the water but they do not grow as an extensive mat of moss. A small section on the west end of the site consists of bare tailings where some areas are limed.

Two spills are associated with the Stanrock Main tailings, referred to by the dam or origin, Dam G (Map 5) and Dam A (Map 6). The Dam G spill passes through a forested area and down a rocky creek through two swampy openings into Quirke Lake. As a result of this, four small tailings areas are exposed at present. The northern area has a pond in which filamentous algae grow. The water level of the ponds is controlled by a dam and pumping system which transports excess water back into the Stanrock tailings treatment pond. The tailings here are bare although occasionally dead wood supports some tree growth.

Below the pumping station, the rocky creek bed is densely covered with leaf litter and attached algae. The second and third open areas, into which the creek runs, are invaded by a mixture of sedges and *Typha* along the edges of the forests. In the third area, closest to Quirke Lake, the *Typha* stands are quite extensive leaving only a small centre of bare tailings exposed. The delta of the tailings spill is free of vegetation.

The Dam A spill (Map 6) occurred through a completely rocky narrow creek. On the banks of the creek, tailings that have been washed into the forest have left barren rocks behind. The creek is intensely green with algae, identified as the acid tolerant species *Euglena mutabilis*. The spill covered a wider section in the eastern part of this site where mixed stands of *Typha* and sedges survive.

3.1.2.2 Limed tailings sites. Stanrock Main (Map 7), one of the three largest tailings sites in the Elliot Lake area studied, was stabilized with lime in 1978. In the eastern half of the tailings pond, extensive islands of moss cover and tree seedlings have established.



Scale: 1 cm = 45.6 m

Area: 0.013 km^2

LEGEND

☐	bare tailings	◐	mixed *Typha* and sedge
✿	moss cover	▨	rock and gravel
●	*Typha* colonies only	≋	water
○	sedge colonies only	⊤	dam

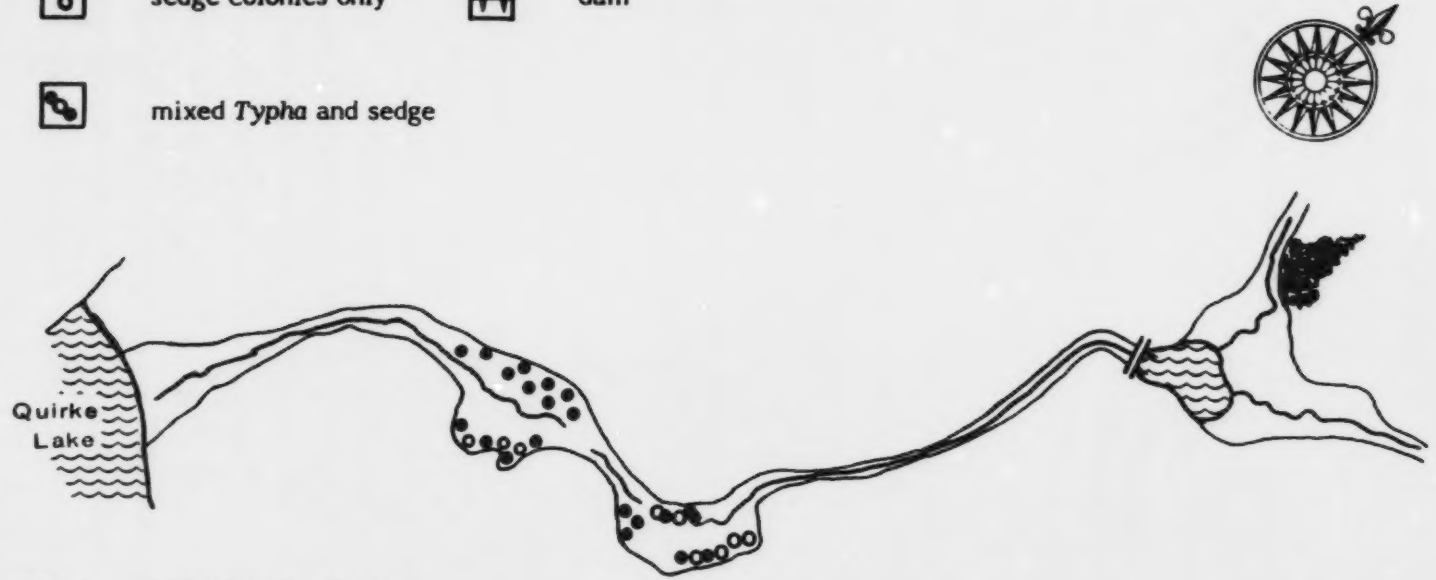
MAP 4 PANEL DAM A

Scale: 1 cm = 41.2 m

Area: 0.02 km^2

LEGEND

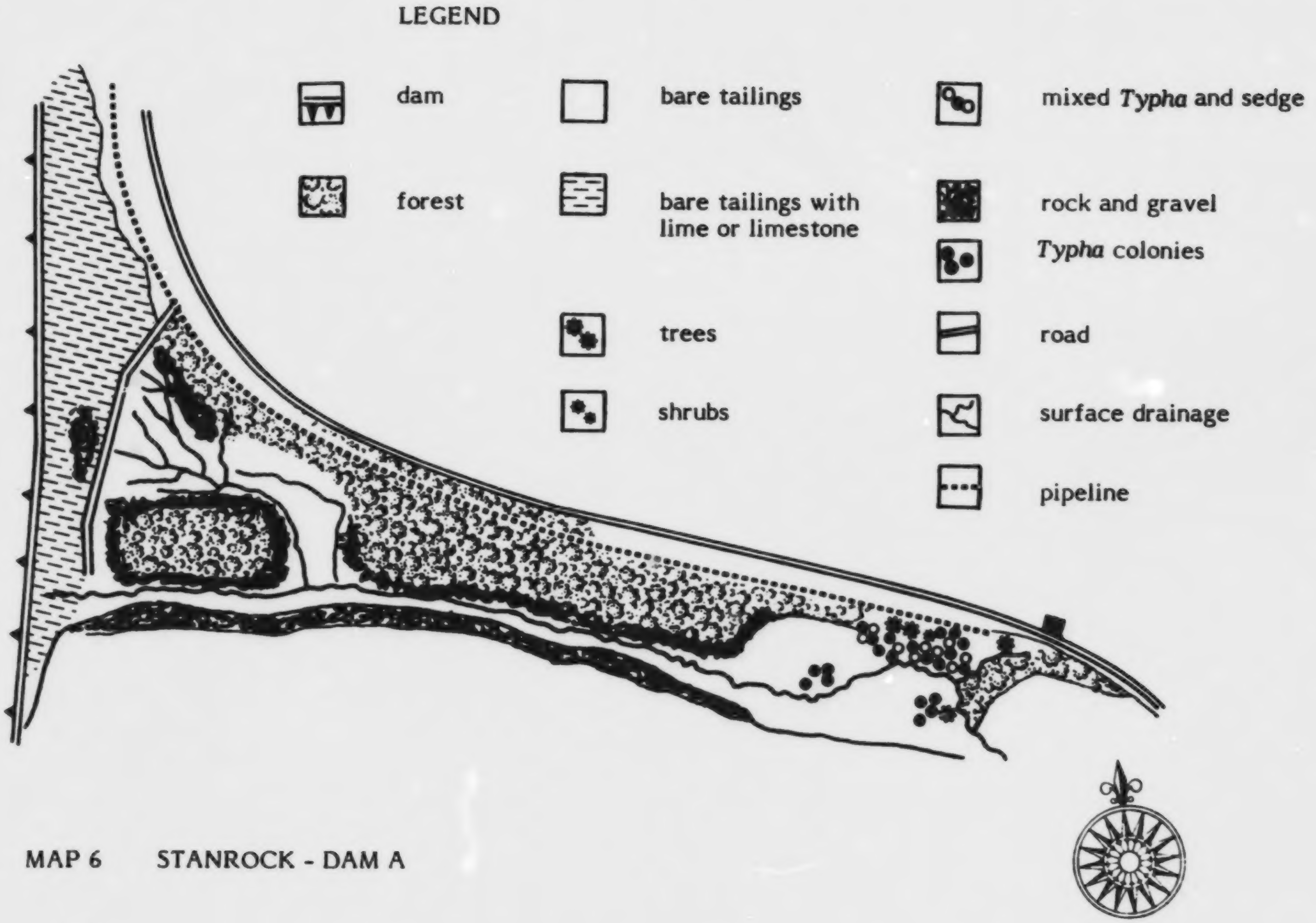
☐	bare tailings	■	rock and gravel
●	*Typha* colonies only	≋	water
○	sedge colonies only	⊓	dam
◐	mixed *Typha* and sedge		



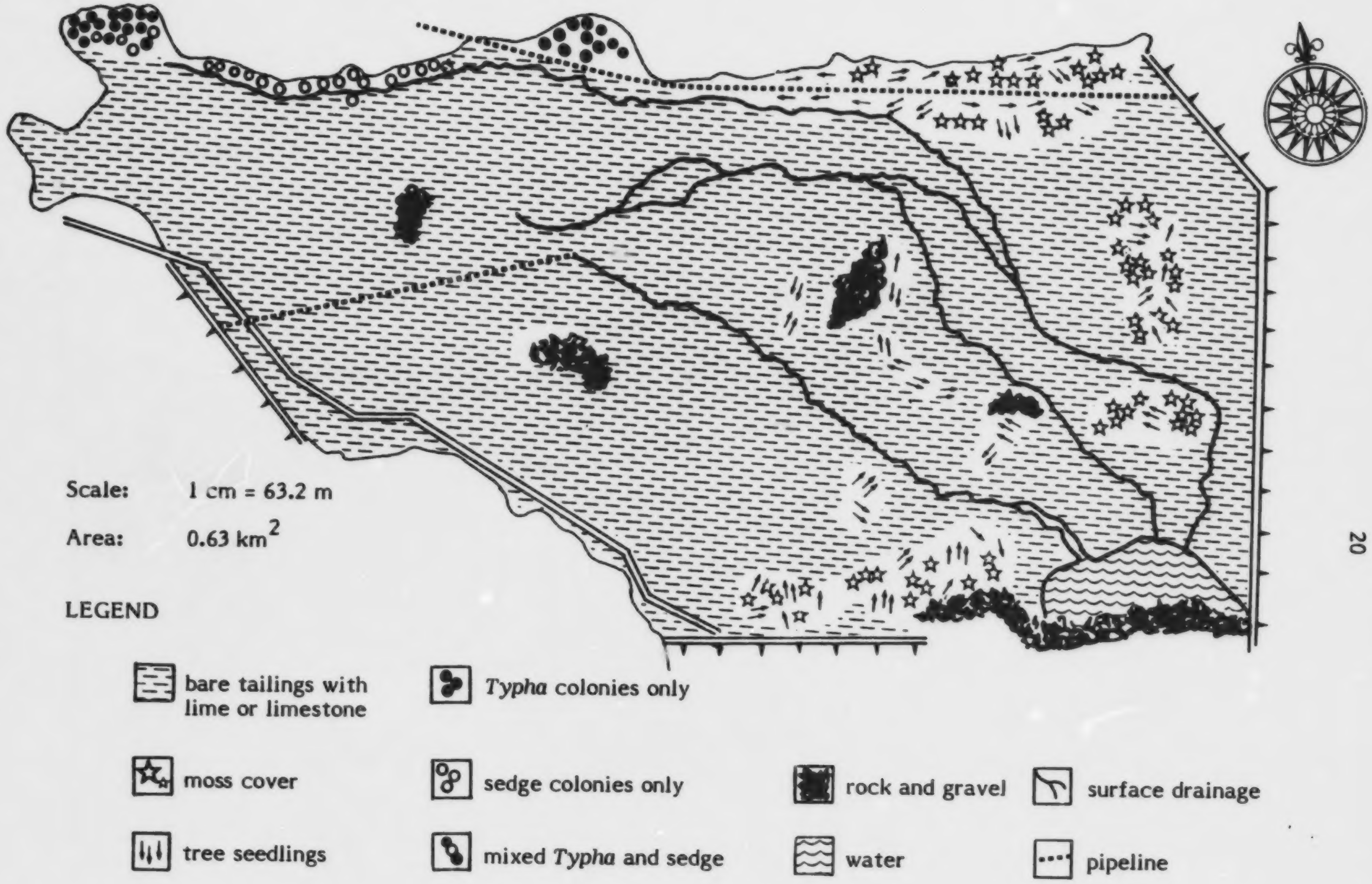
MAP 5 STANROCK - DAM G

Scale: 1 cm = 42.4 m

Area: 0.06 km^2


LEGEND
dam
forest
bare tailings
bare tailings with lime or limestone
trees
shrubs
mixed *Typha* and sedge
rock and gravel
Typha colonies
road
surface drainage
pipeline

MAP 6 STANROCK - DAM A


Scale: 1 cm = 63.2 m
Area: 0.63 km²
LEGEND
bare tailings with lime or limestone
moss cover
tree seedlings
Typha colonies only
sedge colonies only
mixed *Typha* and sedge
rock and gravel
water
road
surface drainage
pipeline
dam

MAP 7 STANROCK MAIN

A similar cover has invaded the edges, particularly the northern and the southeastern edges. The northwesterly edge is sparsely covered by sedges and some *Typha* stands. The western portion of the tailings pond is devoid of vegetation, possibly a reflection of the drainage of the site. In the eastern portion, a small puddle of water, surface drainage and the texture of the surface indicate higher water content in this area. Islands of rocks are surrounded by tree seedlings often associated with a moss cover. The tree seedlings appear to occur mainly on the wind shadow side of the rock islands.

Crotch Lake was also stabilized by application of limestone (Map 8). The surface characteristics are very similar to Stanrock Main. Tree seedlings around the rock islands with moss covers are prominent. *Typha* stands are found on the perimeter of the exposed tailings. The water flowing from the east end over the tailings into a creek to the west are neutralized in a treatment facility.

Some areas of the Crotch Lake tailings were used as experiemental plots for revegetation. These plots are relatively rich in vascular plant species. Trees have reached a height of approximately 1 to 1.5 m. Moss cover, grass species and a striking diversity of macrofungi survive on these experimental areas.

3.1.2.3 Amended tailings sites. Recently, Lacnor (Map 9) and Olive (Map 10) sites were amended. These tailings are well covered with introduced vegetation although some areas have remained bare due to drainage problems. Of particular interest on these sites is the absence of trees, tree seedlings and moss cover. The revegetated cover is alive and no areas of dead grass were noted.

Typha and sedge colonize the tailings beaches and some pockets of the tailings where sufficient moisture is retained. The water in Olive Lake is invaded by aquatic mosses, *Sphagnum cuspidatum* and *Drepanocladus fluitans*, forming an extensive cover in the pond. No moss invasion was noted in the water body of Lacnor.

On the Nordic West Arm (Map 11), the revegetation program was started in 1975 on the western portion of the site. Experimental planting of conifers and other trees was pursued in the southwestern section (Murray, 1978). These trees are, therefore, not of the same origin as the trees recorded on the other maps. A larger patch of dead grass is situated below the western dam and a further bare tailings area remains in the western section of the Nordic West Arm.

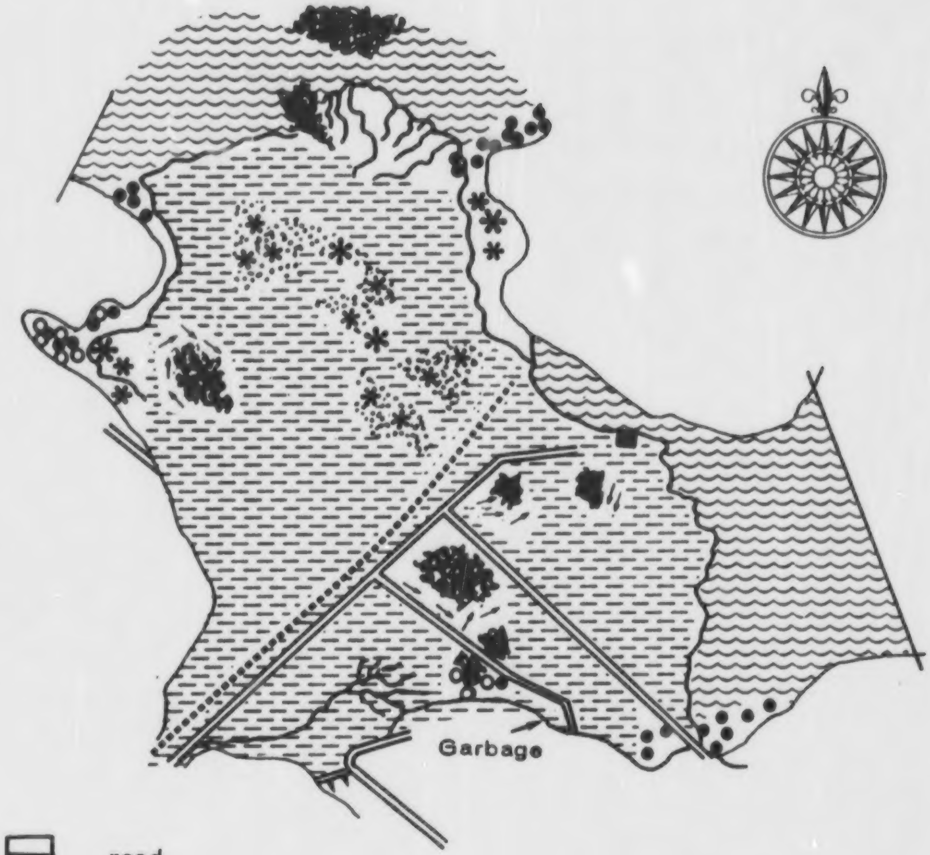
The northwesterly border of the tailings pond is separated from the revegetated area by a creek. This thin band of tailings is invaded by moss cover, trees

Scale: 1 cm = 93.2 m

Area: 0.53 km^2

LEGEND

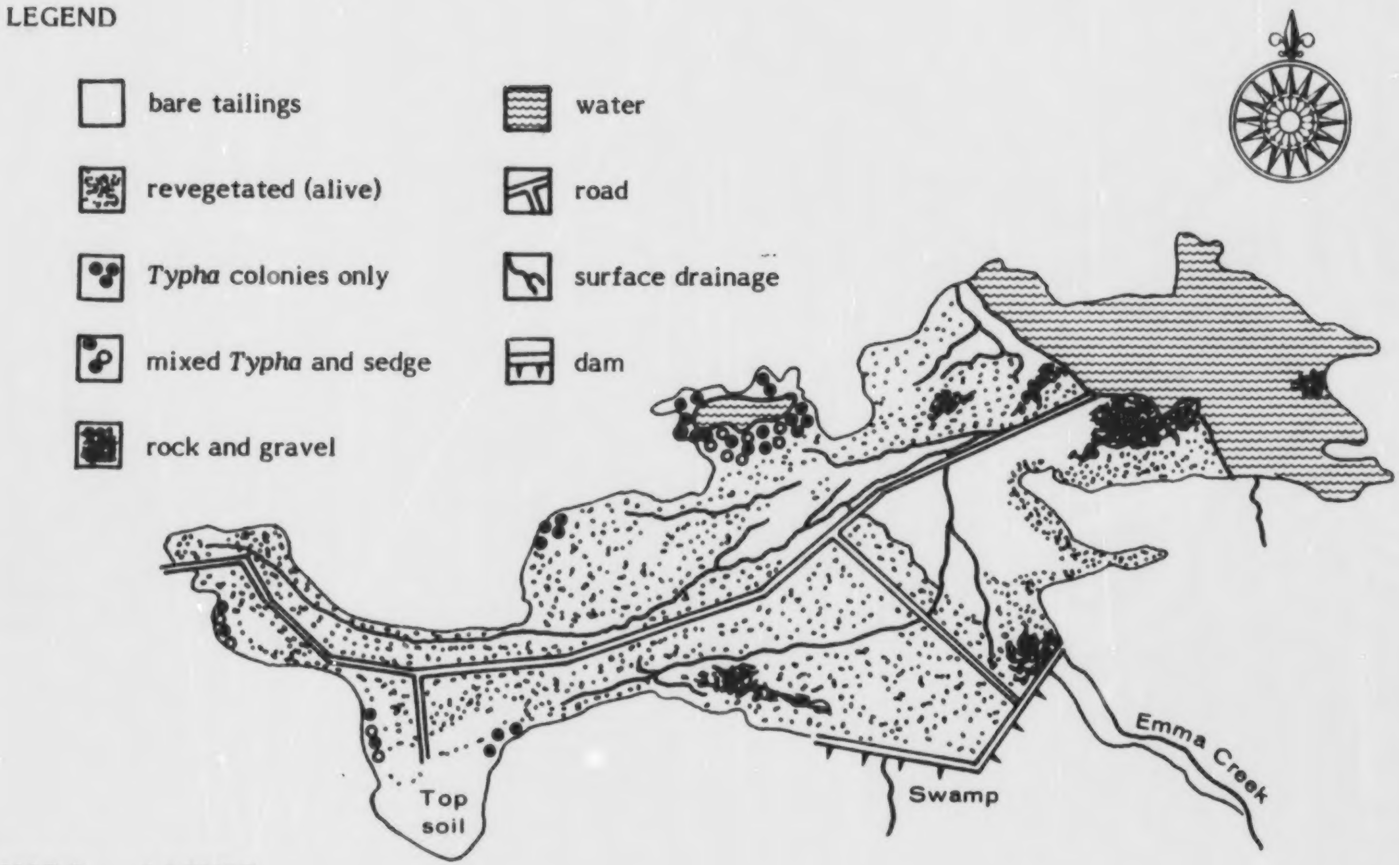
▤	bare tailings with lime or limestone
▩	revegetated (alive)
*	trees
↓	tree seedlings
●	*Typha* colonies only
○	mixed *Typha* and sedge
■	rock and gravel
≋	water
⟋	surface drainage
═	road
┄	pipeline
╤	dam



MAP 8 CROTCH LAKE

Scale: 1 cm = 73.1 m

Area: 0.24 km^2


LEGEND
bare tailings
revegetated (alive)
Typha colonies only
mixed Typha and sedge
rock and gravel
water
road
surface drainage
dam
Top soil
Swamp
Emma Creek

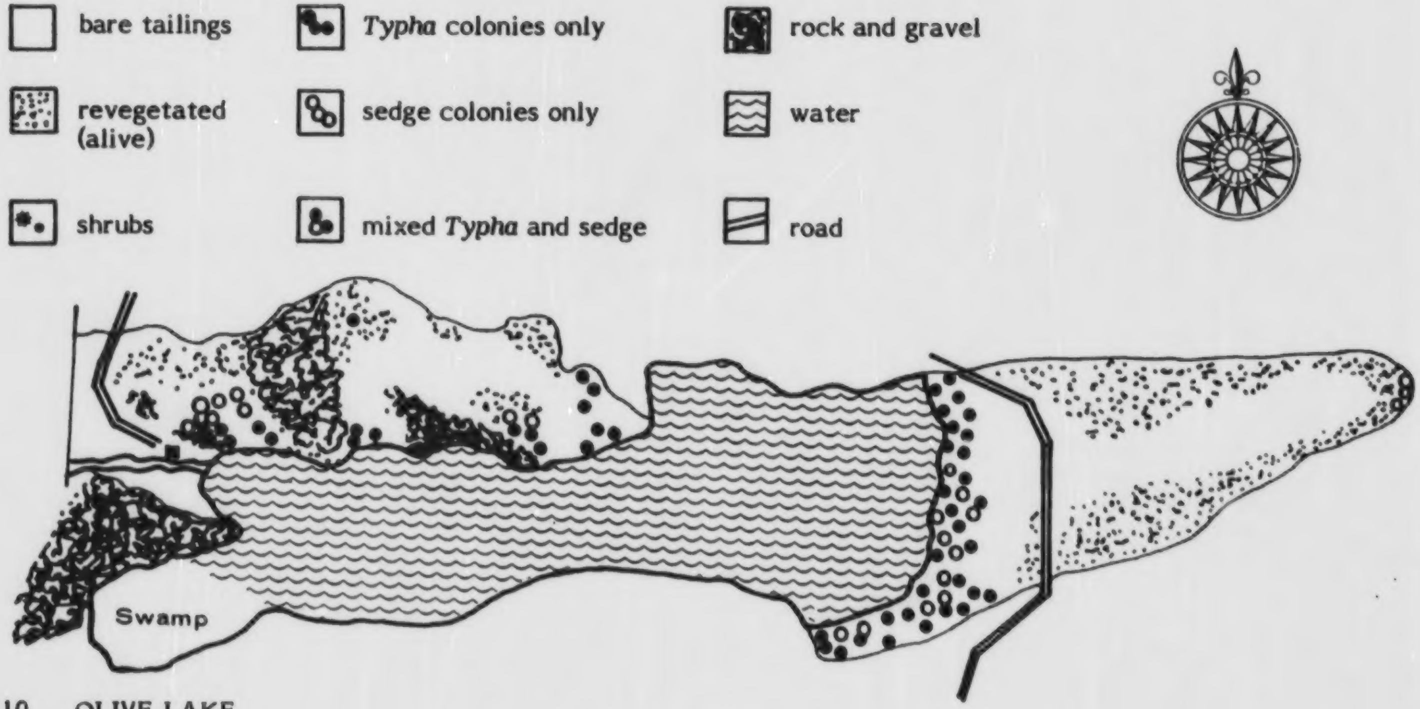
MAP 9 LACNOR

Scale: 1 cm = 48.7 m

Total area: 0.14 km^2

East tailings: 0.03 km^2

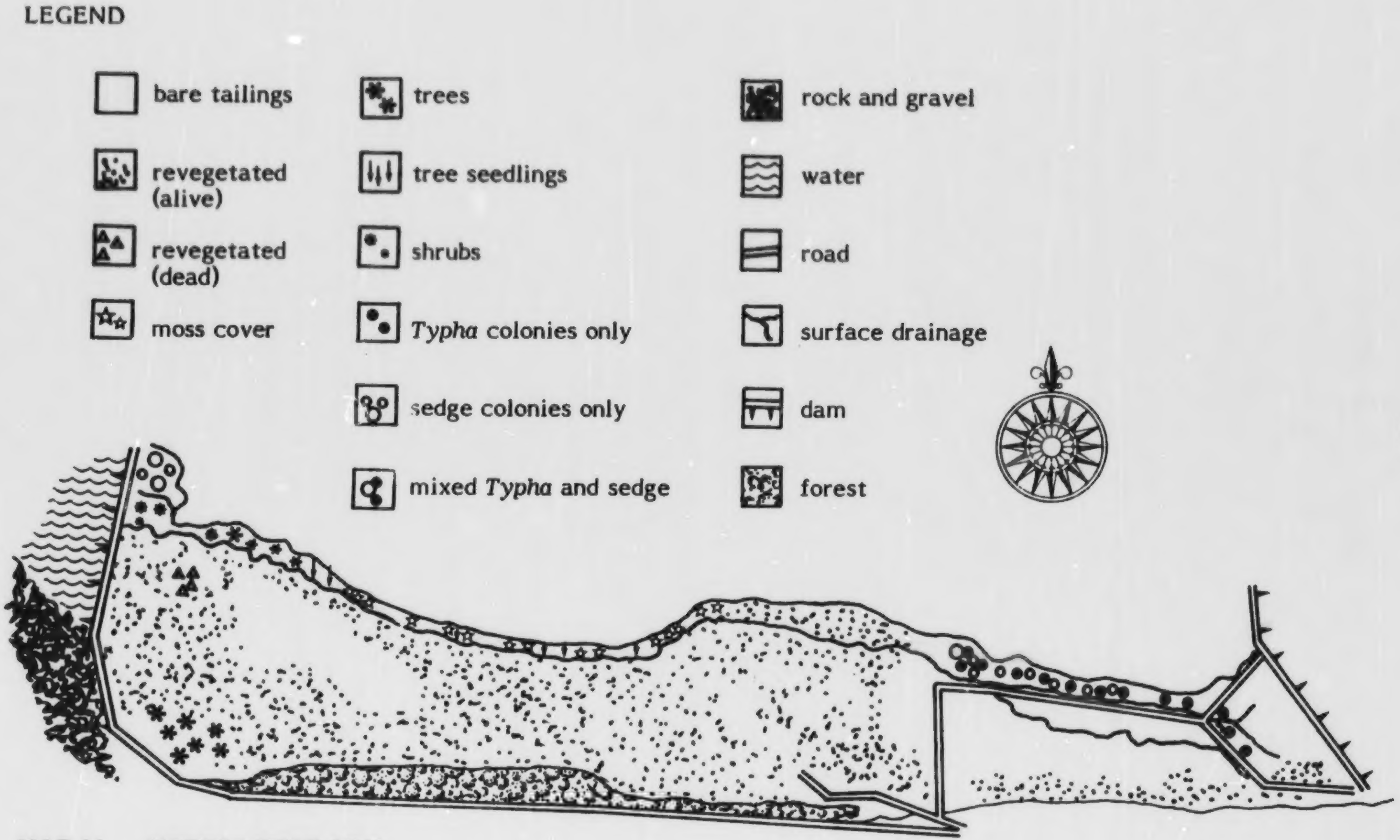
Northwest tailings: 0.02 km^2


LEGEND
☐ bare tailings
▨ revegetated (alive)
● shrubs
● *Typha* colonies only
○ sedge colonies only
● mixed *Typha* and sedge
■ rock and gravel
≋ water
▨ road
Swamp

MAP 10 OLIVE LAKE

Scale: 1 cm = 55.1 m

Area: 0.16 km^2


LEGEND
bare tailings
revegetated (alive)
revegetated (dead)
moss cover
trees
tree seedlings
shrubs
Typha colonies only
sedge colonies only
mixed Typha and sedge
rock and gravel
water
road
surface drainage
dam
forest

MAP 11 NORDIC WEST ARM

and tree seedlings, with mixed *Typha* and sedge colonies in the eastern part behind the creek. A rare occurrence on the tailings is a stand of *Phragmites australis*.

The Nordic Main tailings site (Map 12) is the oldest revegetated site with amelioration having been carried out in sub-sections since 1970. Nordic Main has the most extensive cover of trees but no tree seedlings were noted. The tree stands often exhibit a regular patterns by forming rows. Extensive moss carpets are found within the revegetated sections associated with trees and grasses.

The southwesterly section of Nordic Main has received sewage sludge. In this area, shrubs and potatoes are interspaced with bare sludge areas and revegetated cover. A small colony of mixed *Typha* and sedges is located at the northwesterly edge of the tailings pond where a creek provides moisture. Nordic Main is an extremely diverse tailings pond; it is well revegetated and the surface cover reflects the extensive amelioration work that has taken place in the past years.

A site resembling the diversity of Nordic Main in surface characteristics is the Lower Williams (Map 13). This tailings site is essentially a spill area, where the surface was reclaimed by using till as a cover (Murray, 1979). The trees on this site also grow in a row type pattern similar to the Nordic Main site. Rows or stands of trees are located on the west and east sides of a dead revegetated area. Sedges on the edges of this centre area indicate the existence of moisture. At the end of the season in 1980 the dead vegetation was covered with top soil.

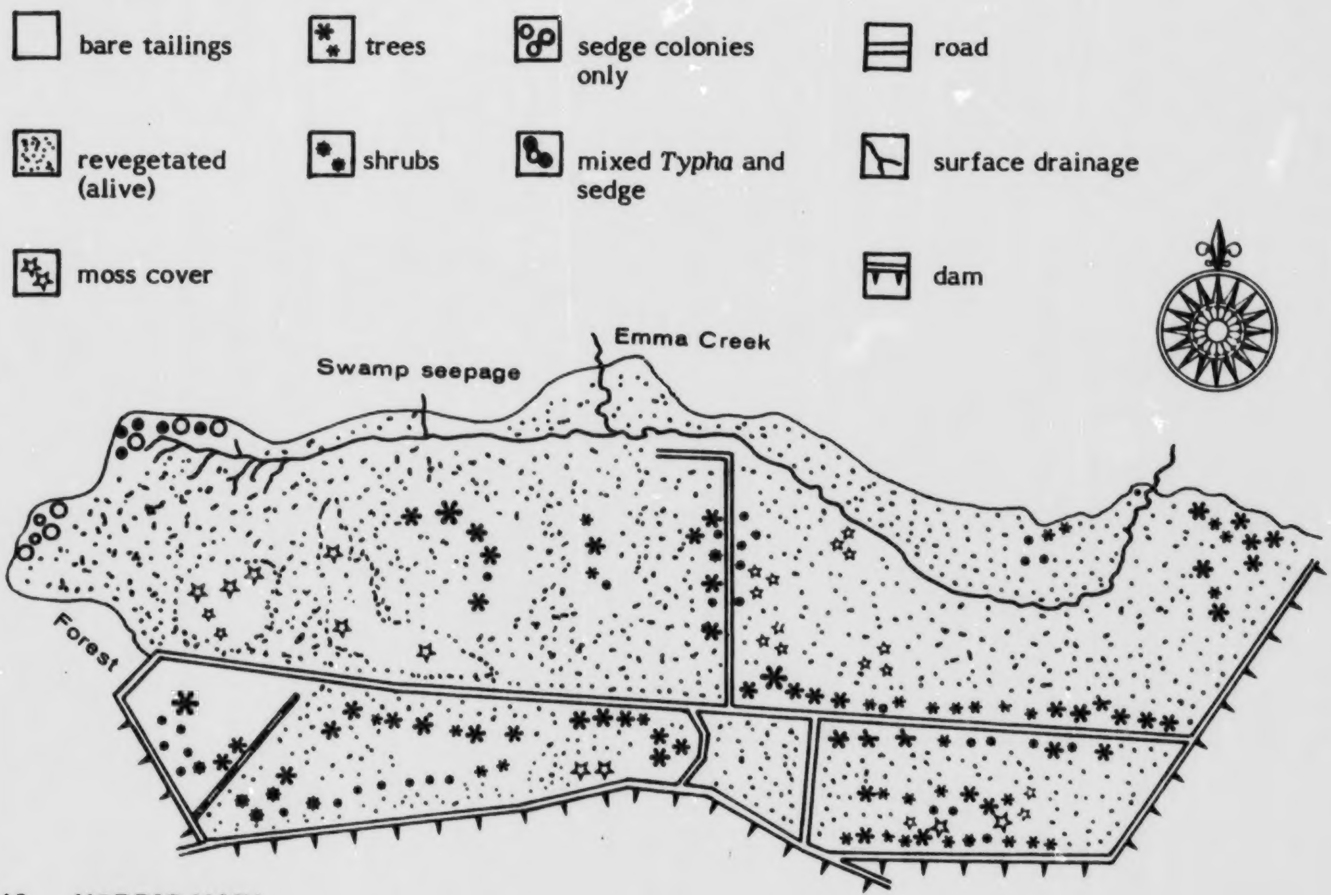
A *Typha* stand abuts the revegetated cover of the Lower Williams sites. On all other sites the revegetated grass cover was separated by a belt of bare tailings from the *Typha* stands. A second extensive stand of *Typha* mixed with sedges grows in a seepage area on the south side of the road before the treatment facility. Moss cushions mixed with trees cover the gravelly northeastern shores of the pond.

The reclamation scheme of the Lower Williams site differs from other tailings surfaces. Not only was a cover consisting of till and overburden provided to establish vegetation but, seepage water was also diverted from the site and treated with NaOH. Thus, Lower Williams is in effect a reclaimed treatment pond.

3.1.3 **The Bancroft Sites.** Madawaska tailings pond No. 2 is described in detail by Stokes and Kalin (1978). This site has been covered with overburden and the seeding of agricultural species and fertilization of the tailings pond sections have been carried out. Large areas of the pond are well covered with indigenous vegetation.

Scale: 1 cm = 93.2 m

Area: 0.85 km^2


LEGEND
bare tailings
revegetated (alive)
moss cover
trees
shrubs
sedge colonies only
mixed *Typha* and sedge
road
surface drainage
dam
Swamp seepage
Emma Creek
Forest

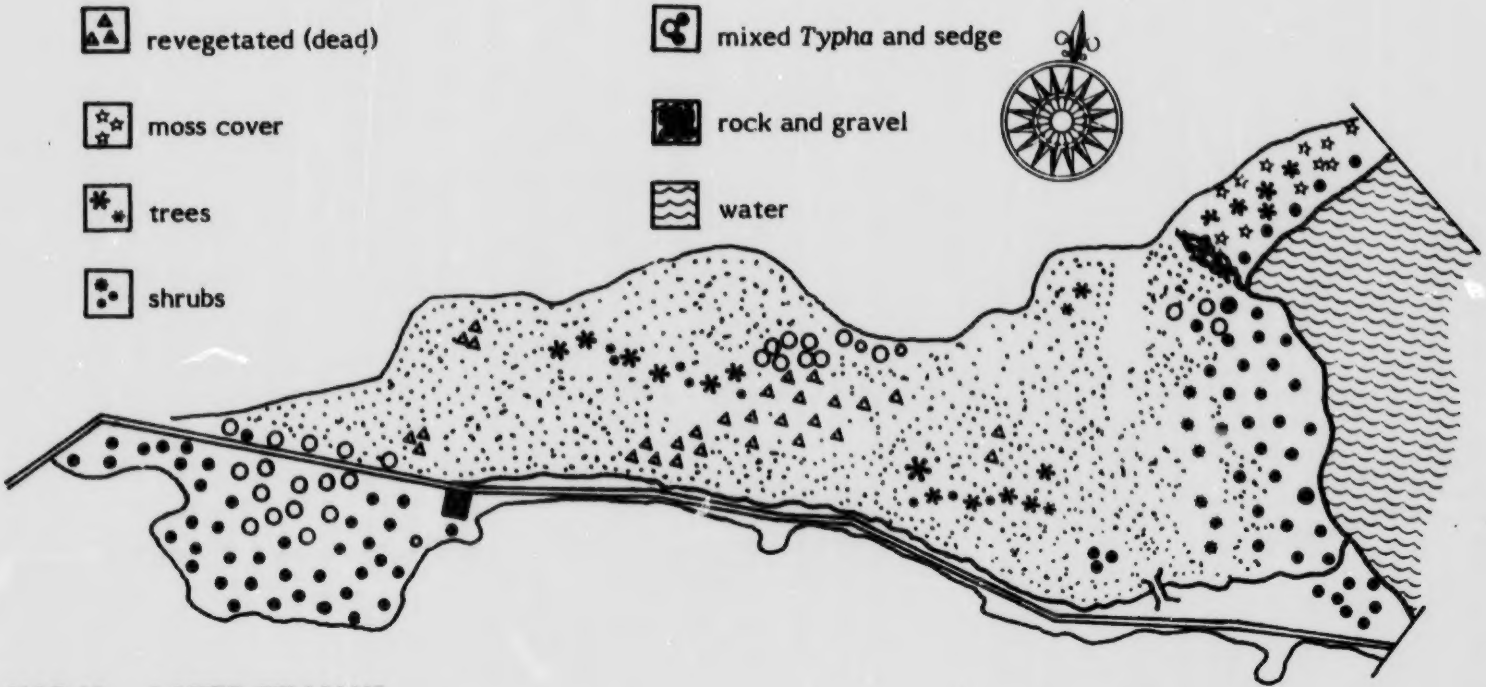
MAP 12 NORDIC MAIN

Scale: 1 cm = 17.9 m

Area: 0.02 km^2

LEGEND

- ☐ bare tailings
- ▨ revegetated (alive)
- ▲ revegetated (dead)
- ☆ moss cover
- ✱ trees
- • shrubs
- ● *Typha* colonies only
- ○ sedge colonies only
- ◉ mixed *Typha* and sedge
- ■ rock and gravel
- ≋ water
- ☰ road



MAP 13 LOWER WILLIAMS

The Auger Lake (Map 14) and Bicroft Proper (Map 15) sites have not been amended in any way since their abandonment. The vegetation is entirely indigenous and consists of trees, moss, *Typha* and sedges. Areas of bare tailings stretch between denser vegetation belts which border the water on the tailings. On the shores of both sites, *Typha* and sedge colonies extend somewhat along the creeks which run into the bare tailings areas.

Bicroft Proper (Map 15) has two areas with shrubs. An island, which appears to be a remnant of a bog and is covered densely with *Sphagnum* moss and labrador tea, is located in the centre of the open water. A small belt of willows survives on the northeastern shoreline; a similar belt of willows occurs on the northeastern shores of Auger Lake (Map 14).

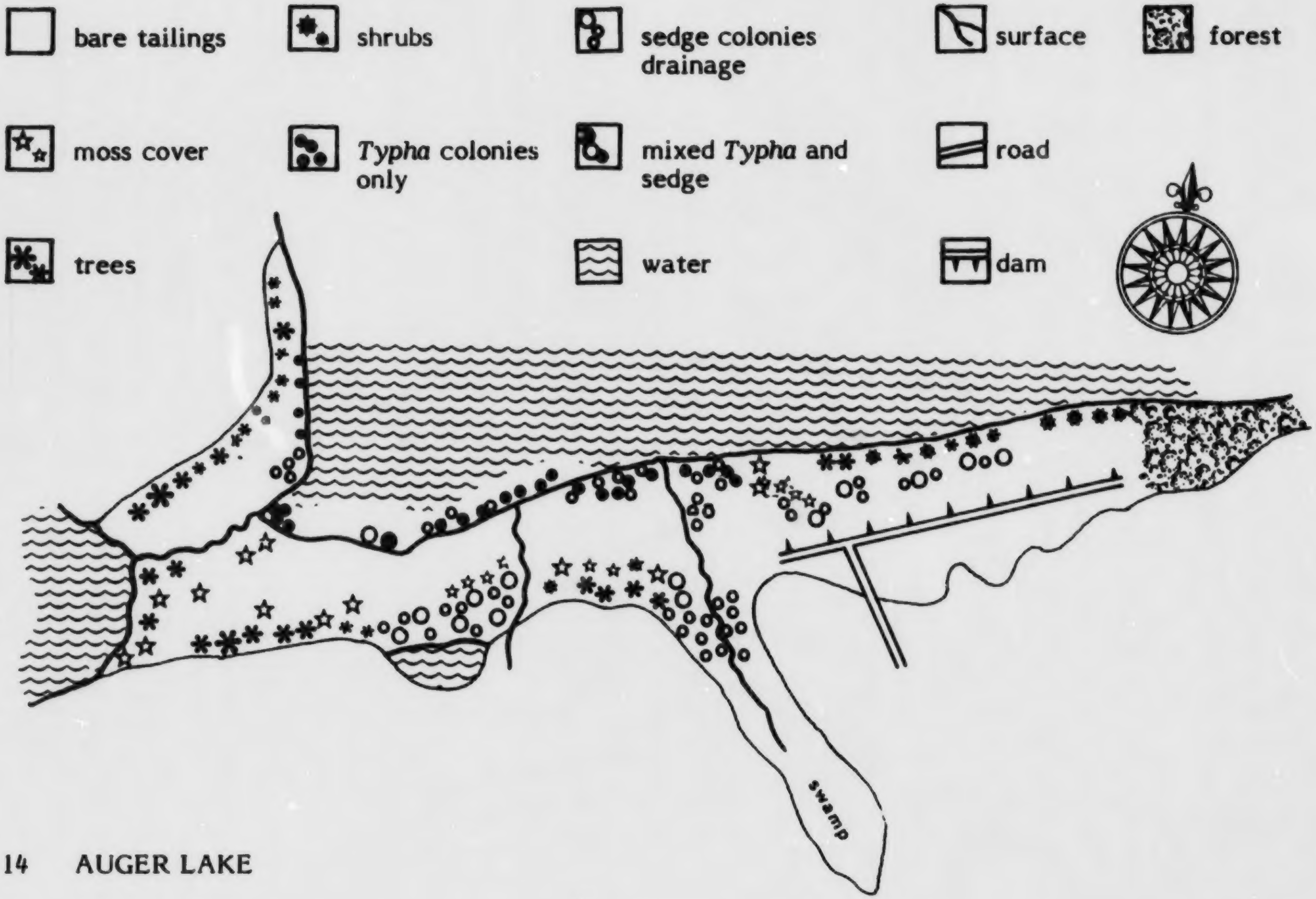
Seepage and overflow from decant structures leave Auger Lake in a southerly direction and Bicroft Proper in a northerly direction (Map 2). The water runs into a swamp referred to as Bicroft Swamp (Map 16). The site has also received some tailings material that was probably deposited during a break in the slurry pipe that transported the tailings to Auger Lake. At the beginning of the investigations in 1979, several large areas of exposed tailings were located on the southeastern side of the road. Beaver activity on the site resulted in flooding of the Bicroft Swamp by the end of the 1980 season.

There are two different types of vegetation cover found on the Bicroft Swamp site. Behind a rock berm on the west side, dense grass, sedges and *Typha* are saturated with seepage water from Auger Lake. Most of the trees are dead in this area. A *Typha* colony grows on the east side of the berm. Dry tailings are covered with moss and trees are growing on these areas of the Bicroft Swamp site.

Dyno, the fourth tailings site in Bancroft, is very similar in appearance to Bicroft Swamp. On Dyno, most of the tailings are covered by wetland vegetation. The Dyno tailings (Map 17) were deposited in the northern half of Farrell Lake which was divided by a dam before the tailings deposition. Below the dam, in the remaining part of Farrell Lake, iron precipitation is extensive in the shallow water. This site is almost completely covered with sedges; only in the northwest part do some small areas remain as bare exposed dry tailings. The cover of trees and shrubs along the west edge of the tailings pond is relatively dense. Indeed, Dyno is a tailings site whicn exemplifies the capability of wetland vegetation to invade inactive uranium mill tailings extremely well.

Scale: 1 cm = 22.2 m

Area: 0.018 km^2

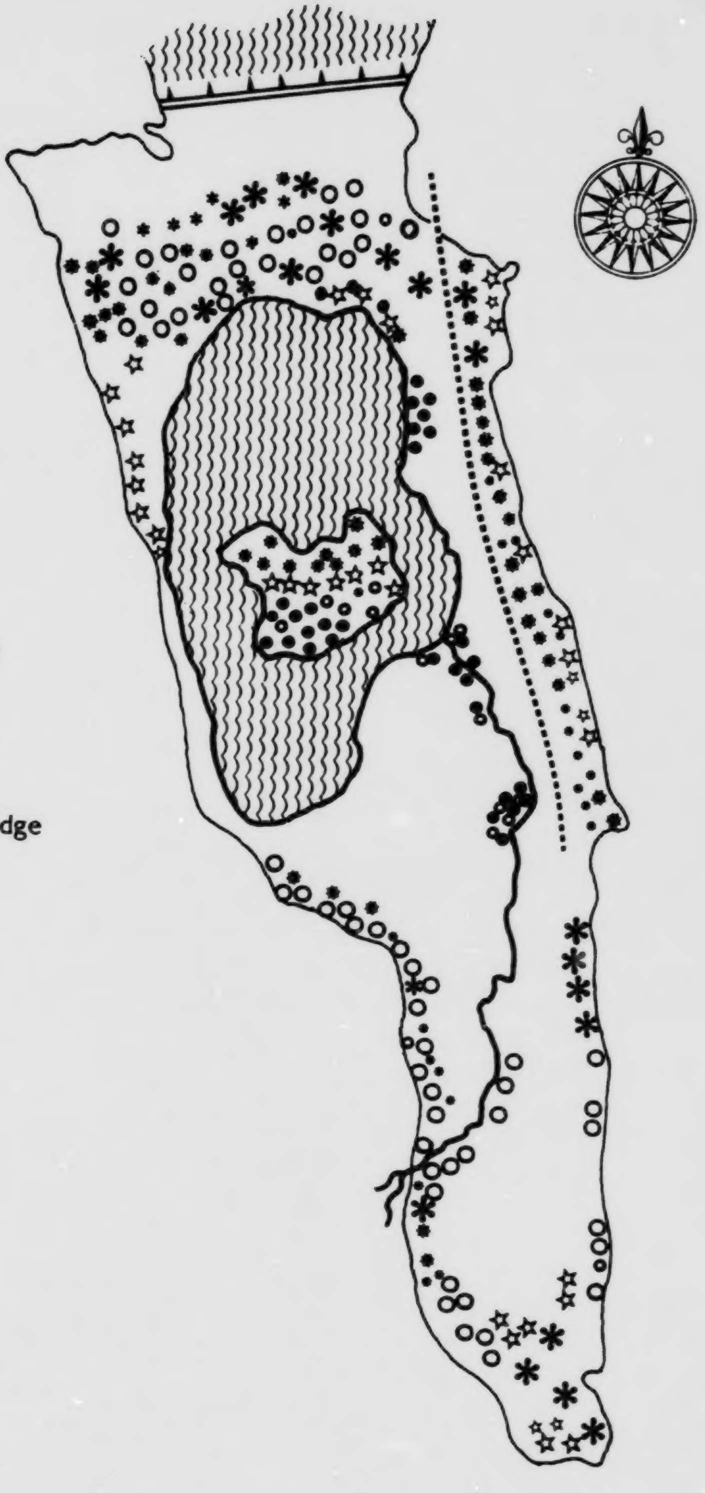

LEGEND
bare tailings
shrubs
sedge colonies
drainage
surface
forest
moss cover
Typha colonies only
mixed *Typha* and sedge
road
trees
water
dam
swamp

MAP 14 AUGER LAKE

Scale: 1 cm = 24.1 m
Area: 0.038 km^2

LEGEND

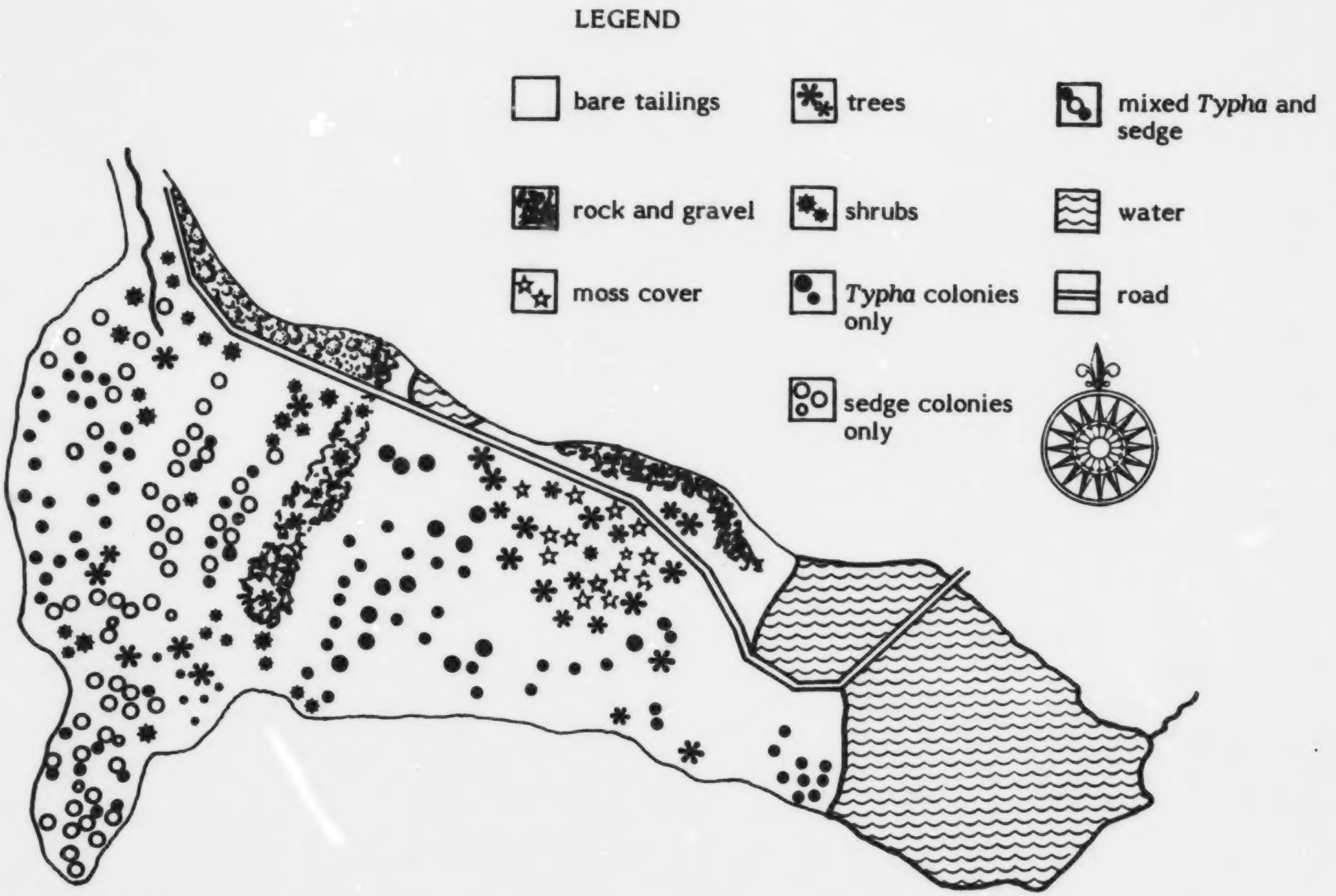
- ☐ bare tailings
- ☆ moss cover
- ✱ trees
- ✸ shrubs
- ● *Typha* colonies only
- ○ sedge colonies only
- ●○ mixed *Typha* and sedge
- ≋ water
- ⌐ surface drainage
- ┄ pipeline
- ╤ dam



MAP 15 BICROFT PROPER

Scale: 1 cm = 18.3 m

Area: 0.065 km^2

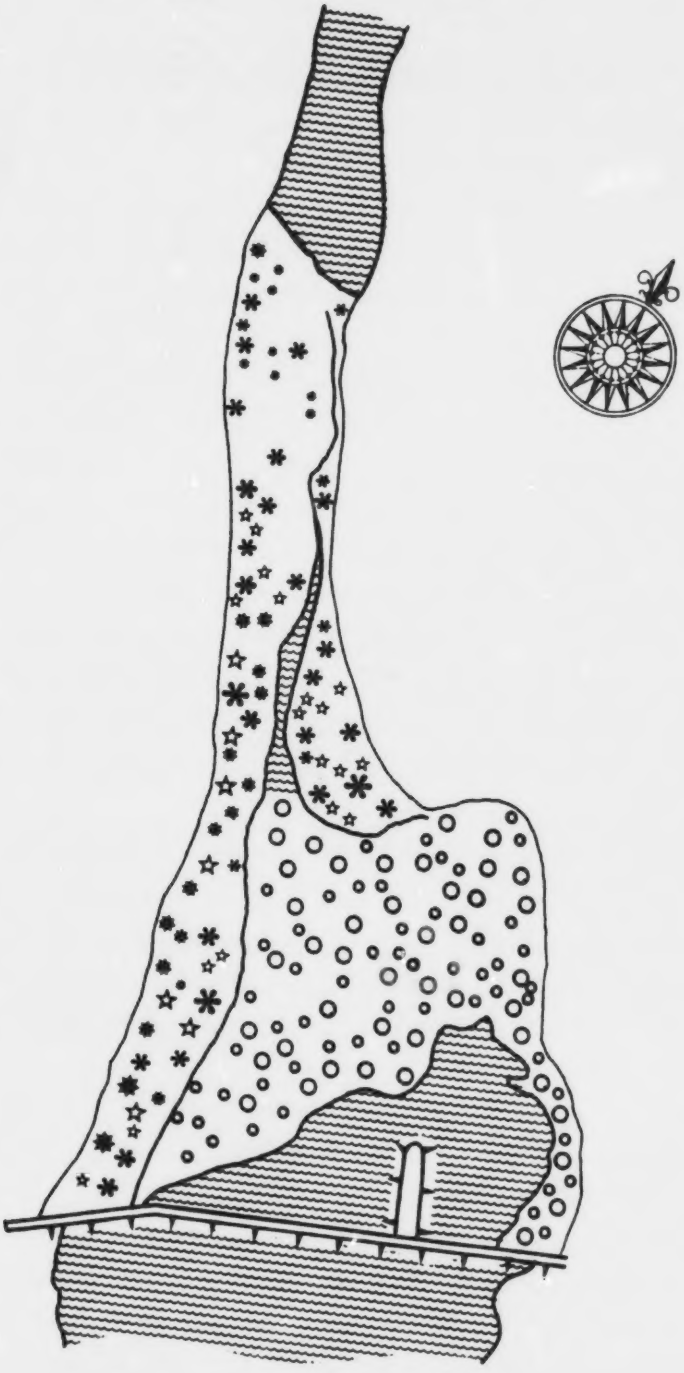

LEGEND
bare tailings
rock and gravel
moss cover
trees
shrubs
Typha colonies only
sedge colonies only
mixed *Typha* and sedge
water
road

MAP 16 BICROFT SWAMP

Scale: 1 cm = 39.1 m
Area: 0.027 km^2

LEGEND

- ☐ bare tailings
- ☆ moss cover
- ✱ trees
- ✸ shrubs
- ◎ sedge colonies only
- ▤ water
- ⌒ surface drainage
- ▭ dam



MAP 17 DYNO

3.1.4 Abandoned Uranium Mill Tailings Surfaces as a Whole. The surface characteristics described earlier and mapped for each site provide site-specific information. It is now possible to identify common characteristics of abandoned tailings sites.

During the survey of the tailings sites, vascular plants were collected and identified. Seeding records allow differentiation of indigenous and introduced plants. The seeded species for the revegetated sites are summarized in Table 3. *Festuca rubra* and *Lotus corniculatus* were seeded on all sites, in addition to at least one other species per site. The Madawaska No. 2 tailings pond was seeded with the largest variety of species.

Most tailings sites require extensive ameliorative measures since grass covers cannot be established on unprepared surfaces. The type of amendments utilized to establish a grass cover are summarized in Table 4. The data compiled in this table are an indication of the magnitude of the amelioration efforts. The existing covers are clearly a result of extensive experimentation. On the Madawaska No. 2 tailings site, the chemical characteristics differ drastically from the other sites surveyed.

One of the objectives of revegetation programs is to establish a cover on the tailings which allows indigenous species to invade the surfaces. The invasion of indigenous species occurring on the tailings sites after different amendments and on sites with no amendments can be compared.

All vascular plant families which have been found to occur on most tailings sites are given in Table 5. Ten families survive on the tailings; three of them are predominantly represented by wetland species (Cyperaceae, Juncaceae and Typhaceae), and three by shrubs or trees (Salicaceae, Betulaceae and Rosaceae). Typical wasteland or road-site herbaceous plants are represented by members of the Compositae, Polygonaceae and Equisetaceae families. The grasses (Gramineae) are mainly species seeded on the tailings; only a few native or naturalized species of this family are found.

A detailed record of the occurrence of all genera is given for abandoned sites in the Elliot Lake and Bancroft areas (Table 6). The species name is only given if it is the sole representative of the genus. The species identified in the other genera are given in Table 7. In total, 20 families of vascular plants occur on abandoned or inactive tailings. However, eight of them (Caryophyllaceae, Cupressaceae, Droseraceae, Labiatae, Plantaginaceae, Pinaceae, Myricaceae and Polypodiaceae) are only found on some tailings sites. Their representation in most cases consists of a single species of the genus.

TABLE 3 PLANT SPECIES USED IN SEEDING OF INACTIVE URANIUM MILL TAILINGS SITES

Species	Williams	Nordic	Pronto	Olive	Lacnor	Madawawaska No. 2
Red top *Agrostis gigantea*	X	X		X		
Creeping Red Fescue *Festuca rubra*	X	X	X	X	X	X
Kentucky bluegrass *Poa pratensis*		X	X		X	X
Canada bluegrass *Poa compressa*		X	X			
Reed canary grass *Phalaris arundinacea*					X	
Birds-foot trefoil *Lotus corniculatus*	X	X	X	X	X	X
Timothy *Phleum pratense*						X
Oat *Avena sativa*						X
Clover*						X
Rye*						X
Rape grass*						X

* Latin names not available from the records.

Several interesting observations can be made when both tables are studied simultaneously. Three families occur locally. Pines and cedars generally do not occur in Elliot Lake, but they are found on all the Bancroft sites with the exception of Bicroft Swamp. An extensive representation of Fabaceae on the amended sites at Elliot Lake is apparent. All other families exhibit a sporadic but universal occurrence. Caryophyllaceae, Plantaginaceae, Labiatae, Myricaceae and Droseraceae occur on only two or three sites and are represented by one species alone.

Many species were identified for the families Gramineae, Juncaceae, Cyperaceae and Salicaceae. However, within these four families, only two species, *Carex*

TABLE 4 ESTIMATED SUMMARY OF INITIAL AMENDMENTS USED TO REVEGETATE ABANDONED URANIUM MILL TAILINGS (1970-1980) (Source: personal communication, Rio Algom Ltd., Denison Mines Ltd., and Madawaska Mines Ltd.)

Location	Neutralizing Agent[a] (t/ha)	Fertilizer[b] (t/ha)	Other Important Amendments
Nordic	22-112	experimental (0.25/yr)[c]	sewage sludge mulches
Williams	44	0.77	till
Olive	22-67	0.56 (0.25/yr)	none
Lacnor	45-67	0.45 or 0.11 (0.25/yr)	none
Crotch	experimental plots	experimental plots	sawdust with sewage sludge
Stanrock	25	none	none
Pronto	22-67	0.77 (0.25/yr)	none
Madawaska No. 2	none	0.14	run of mine waste rock

[a] form of neutralizing agents used: lime slurry, limestone, burnt lime, soda ash and ammonia

[b] fertilizer types used: 6-24-24, 5-20-20, 18-46-0, 1-20-20, 0-46-0, rock phosphate and ammonium nitrate

[c] numbers in brackets are yearly applications after seeding

crawfordii and *Scirpus cyperinus* belonging to the family Cyperaceae, were found on most uranium mill tailings. No single Gramineae species occurred consistently on the inactive tailings. A more detailed survey could possibly identify some indigenous grass species; however, no species are presently dominant.

The summaries of occurrences of vegetation on inactive tailings (Tables 6 and 7) indicate essentially that the wetland species and some tree species are the only groups of plants which consistently invade the tailings surfaces. In the wetland group, the genera

TABLE 5 FAMILIES OF VASCULAR PLANTS REPRESENTED ON MOST OF THE URANIUM MILL TAILINGS IN BANCROFT AND ELLIOT LAKE

Families	Common Names
Betulaceae	Birches
Compositae	Thistles
Cyperaceae	Sedges
Equisetaceae	Horsetails
Gramineae	Grasses
Juncaceae	Rushes
Polygonaceae	Buckwheat
Rosaceae	Roses (shrubby)
Salicaceae	Willows & poplars
Typhaceae	Cattails

Carex and *Juncus* are represented by a large number of species which are known for their ability to adapt to diverse habitats. They are also known as an extremely successful group of plants in temperate climatic regions. All other wetland species identified are also widespread.

Since the volunteer species on inactive tailings are mainly members of wetland habitats, the occurrence of water on the tailings was evaluated. The persistence and survival of this vegetation will ultimately depend on the occurrence of water on these sites. The distribution of water body types on abandoned or inactive tailings is depicted in Figure 1. Percentages are based on the total number of water bodies. From the maps of the tailings sites and discussion of each site, it is evident that one site can have several types of water bodies. The differences between surface drainage (14%) and small puddles (26%) is relatively subjective and not of particular importance since wetland vegetation is not supported by either. In most cases, the larger wetland vegetation stands occur along the shores of the open water category. The climatic conditions of the region suggest that surface water is likely a permanent feature of inactive tailings impoundments. As a consequence, wetland vegetation is important in the evaluation of the long-term effects of uranium mill tailings, particularly in lower portions of the impoundment.

TABLE 6 VASCULAR PLANT OCCURRENCES ON ABANDONED URANIUM MILL TAILINGS

	Elliot Lake									Bancroft				
Plant Species	Nordic Main	Nordic West Arm	Lacnor	Crotch	Williams	Olive	Panel Dam A	Stanrock Main	Stanrock Dam A	Auger Lake	Bicroft Swamp	Bicroft Proper	Dyno	Madawaska
BETULACEAE														
Betula papryifera Marsh.	X	X	X	X	X	X		X		X	X	X	X	X
CARYOPHYLLACEAE														
Cerastium vulgatum L.														X
Gysophila paniculata L.				X										
COMPOSITAE														
Achillea millefolium L.	X	X				X				X	X		X	X
Anaphalis margaritacea (L.) Benth & Hook	X	X		X	X			X		X	X	X	X	
Aster simplex Willd.				X	X			X		X				X
Cirsium vulgare (Savi) Tenore					X						X			X
Hieracium spp.	X												X	X
Rudbeckia hirta L.					X									
Solidago spp.		X	X		X	X				X	X	X	X	X
CUPRESSACEAE														
Thuja occidentalis L.										X		X	X	X
CYPERACEAE														
Carex spp.			X	X	X	X	X	X	X	X	X	X	X	X
Cyperus spp.						X								
Scirpus cyperinus (L.) Kunth.	X		X	X	X	X	X	X		X	X	X	X	X
DROSERACEAE														
Drosera spp.					X								X	
EQUISETACEAE														
Equisetum spp.				X	X	X		X		X	X	X	X	X
FABACEAE														
Lotus corniculatus L.	X	X	X	X	X	X								X
Metilotus spp.		X	X											X
Trifolium hybridum L.	X	X	X			X								X
GRAMINEAE														
Agropyron trachycaulum (Link) Malte.		X								X				
Agrostis spp.	X	X	X	X	X	X		X		X	X	X	X	X
Bromus inermis Leyss.														X
Calamagrostis spp.										X				X
Danthonia spicata (L.) Beauv.												X		
Deschampsia flexuosa (L.) Trin.												X		
Elymus canadensis L.														X
Festuca spp.	X			X		X		X					X	X
Phalaris arundinacea L.	X	X	X											
Phleum pratense L.	X			X	X	X								
Phragmites australis (Cav.) Trinex Steudel		X	X			X								X
Poa spp.	X	X	X	X				X	X	X				
Hordeum jubatum L.		X	X			X								

TABLE 6 VASCULAR PLANT OCCURRENCES ON ABANDONED URANIUM MILL TAILINGS (cont'd)

Plant Species	Elliot Lake									Bancroft				
	Nordic Main	Nordic West Arm	Lacnor	Crotch	Williams	Olive	Panel Dam A	Stanrock Main	Stanrock Dam A	Auger Lake	Bicroft Swamp	Bicroft Proper	Dyno	Madawaska
JUNCACEAE														
Juncus spp.				X	X			X		X	X	X	X	X
LABIATAE														
Lycopus spp.					X									
Mentha arvensis L.													X	
Scutellaria gatericulata L.										X				
MYRICACEAE														
Myrica Gale L.						X				X			X	
ONAGRACEAE														
Epilobium spp.		X	X	X	X			X		X				X
Oenothera spp.		X			X			X		X				X
PINACEAE														
Abies balsamea (L.) Mill				X						X		X	X	
Larix laricina (DuRoi) K. Koch.												X	X	
Picea glauca (Moench) Voss.										X		X	X	X
Pinus strobus L.				X						X		X	X	X
Tsuga canadensis (L.) Carr.										X		X	X	
PLANTAGINACEAE														
Plantago major L.								X						X
POLYGONACEAE														
Polygonum spp.	X				X									X
Rumex spp.	X	X	X	X		X		X		X				X
POLYPODIACEAE														
Pteridium aquilinum (L.) Kuhn				X	X					X		X		
ROSACEAE														
Amelanchier spicata (Lam.) K. Koch										X				
Fragaria spp.										X		X	X	X
Potentilla simplex Michx.					X									
Prunus spp.	X			X	X	X				X			X	X
Rubus strigosus Michx.			X		X					X	X			
Spiraea spp.										X				
SALICACEAE														
Populus spp.	X	X	X	X	X			X		X	X	X	X	X
Salix spp.	X				X	X		X		X		X	X	
TYPHACEAE														
Typha spp.		X	X	X	X	X	X	X	X	X	X	X		X

TABLE 7 LIST OF SPECIES OF VASCULAR PLANTS IDENTIFIED ON ABANDONED TAILINGS[a]

Scientific Name	Common Name
BETULACEAE	BIRCHES
Betula papyrifera Marsh.	Paper Birch
CARYOPHYLLACEAE	PINKS
Gysophila paniculata L.	Tall gypsophyll
Cerastium vulgatum L.	Larger Mouse-ear chickweed
COMPOSITAE	COMPOSITES
Achillea Millefolium L.	Yarrow-milfoil
Anaphalis margaritacea (L.) Benth & Hook	Pearly everlasting
Aster simplex Willd.	Simple aster
Cirsium vulgare (Savi) Tenore.	Bull-thistle
Hieracium floribundum Wimer & Grab.	Smoothish hawkweed
Hieracium pratense Tausch.	Field hawkweed
Rudbeckia hirta L.	Black-eyed Susan
Solidago bicolor L.	Silverrod
Solidago canadensis L.	Canada or rock goldenrod
Solidago graminifolia (L.) Salisb.	Flat-topped goldenrod
Solidago hispida Muhl.	Hairy goldenrod
Solidago juncea Ait.	Early goldenrod
Solidago rugosa Mill.	Wrinkle-leaved, tall, hairy goldenrod
Solidago uliginosa Nutt.	Bog or swamp goldenrod
CYPERACEAE	SEDGES
Carex adusta Boott.	Browned sedge
Carex aquatilis Wahl.	Water sedge
Carex Merritt-Fernaldii Mack.	Pale brown sedge
Carex Crawfordii Fern.	Crawford's sedge
Carex vulpinoidea Michx.	Fox sedge
Carex communis Bailey	Fibrous-rooted sedge
Carex rostrata Stokes	Beaked sedge
Cyperus sp.	Cyperus species unid.
Scirpus cyperinus (L.) Kunth.	Wool-grass
Scirpus validus Vahl.	American great bullrush
Eleocharis olivacea (Torr.) Gl.	Bright-green spike-rush
DROSERACEAE	SUNDEWS
Drosera sp. L.	Sundew
EQUISETACEAE	HORSETAILS
Equisetum arvense L.	Field horsetail
Equisetum variegatum Schleich.	Variegated horsetail
Equisetum hyemale L.	Common scouring-rush
FABACEAE	LEGUMES
Lotus corniculatus L.	Bird's-foot trefoil
Melilotus alba Desr.	White sweet-clover
Melilotus officinalis (L.) Desr.	Yellow sweet-clover
Trifolium hybridum L.	Alsike or Alsatian clover
GRAMINEAE	GRASSES
Agropyron repens (L.) Beaub.	Quack grass
Agropyron trachycaulum (Link) Malte.	Wheat-grass
Agrostis capillaris L.	Colonial bent grass
Agrostis gigantea Roth.	Red top
Agrostis hyemalis (Walt.) B.S.P.	Rough hair-grass (fool-hay)
Agrostis scabra Willd.	Tickle grass

TABLE 7 LIST OF SPECIES OF VASCULAR PLANTS IDENTIFIED ON ABANDONED TAILINGS[a] (cont'd)

Scientific Name	Common Name
GRAMINEAE (cont'd)	GRASSES (cont'd)
Agrostis tenuis Sibth.	Rhode Island bent grass
Festuca pratensis Huds.	Meadow fescue grass
Festuca rubra L.	Red fescue grass
Phalaris arundinacea L.	Reed canary grass
Phleum pratense L.	Timothy (Herd's grass)
Phragmites australis (Cav.) Trinex Steudel	Reed Grass
Poa compressa L.	Canadian bluegrass
Poa pratensis L.	Kentucky bluegrass
Hordeum jubatum (L.) Beauv.	Foxtail barley
Danthonia spicata (L.) Beauv.	Common wild oat-grass
Deschampsia flexuosa (L.) Trin.	Wavy hair-grass
Elymus canadensis L.	Canada lyme-grass
Bromus inermis Leyss.	Awnless Brome-grass
Calamagrostis inexpansa (Gray)	Bog reed-grass
Calamagrostis canadensis (Michx.) Beauv.	Bluejoint grass
JUNCACEAE	RUSHES
Juncus balticus Willd.	Baltic rush
Juncus brevicaudatus (Engelm.) Fern.	Narrow-panicled rush
Juncus bufonius L.	Toad rush
Juncus nodosus L.	Knotted rush
Juncus effusus L.	Common rush
Juncus pelocarpus E. Meyer	Brown-fruited rush
Juncus filiformis L.	Thread rush
Juncus tenuis Willd.	Slender rush
Juncus canadensis J. Gay	Canada Rush
LABIATAE	MINTS
Mentha arvensis L.	Corn mint
Lycopus uniflorus Michx.	Northern bugle-weed
Lycopus americanus Muhl.	Cut-leaved water hoarhound
Scutellaria galericulata L.	Hooded willow-herb marsh or European skullcap
MYRICACEAE	BAYBERRIES
Myrica gale L.	Sweet gale
ONAGRACEAE	EVENING-PRIMROSE
Epilobium angustifolium L.	Fireweed
Epilobium ciliatum Raf.	Willow-herb
Oenothera parviflora L.	Evening-primrose
Oenothera biennis L.	Common evening-primrose
PLANTAGINACEAE	PLANTAINS
Plantago major L.	Common plantain
POLYGONACEAE	SMARTWEEDS
Polygonum sp.	
Polygonum aviculare L.	Knot-grass
Polygonum cilinode Michx.	Bindweed
Polygonum persicaria	Lady's thumb
Rumex acetosella L.	Red or Sheep sorrel
Rumex occidentalis Wats.	Western dock
POLYPODIACEAE	POLYPODIES
Pteridium aquilinum (L.) Kuhn	Bracken fern

TABLE 7 LIST OF SPECIES OF VASCULAR PLANTS IDENTIFIED ON ABANDONED TAILINGS[a] (cont'd)

Scientific Name	Common Name
PINACEAE	PINES
Picea glauca (Moench) Voss.	White spruce
Pinus strobus L.	White pine
Larix laricina (DuRoi) K. Koch.	Tamarack
Abies balsamea (L.) Mill.	Balsam fir
Tsuga canadensis (L.) Carr.	Hemlock
CUPRESSACEAE	CEDARS
Thuja occidentalis L.	White Cedar
ROSACEAE	ROSES
Amelanchier spicata (Lam.) K. Koch.	Low June berry
Prunus pennsylvanica L.	Pin cherry
Prunus virginiana L.	Choke cherry
Rubus strigosus Michx.	Red raspberry
Spiraea tomentosa L.	Hardhack
Spiraea latifolia (Ait.) Borkh.	Meadow-sweet
Potentialla simplex Michx.	Decumbent five-finger
Fragaria vesca L.	Hedge strawberry
Fragaria virginiana Duchesne.	Scarlet strawberry
SALICACEAE	WILLOWS
Populus balsamifera L.	Balsam poplar
Populus grandidentata Michx.	Large tooth aspen
Populus tremuloides	Trembling aspen
Salix bebbiana Sarg.	Beaked willow
Salix lucida Muhl.	Shining willow
Salix petiolaris Sm.	Slender willow
Salix interior Rowlee	Sandbar-willow
Salix discolor Muhl.	Pussy-willow
Salix humilis Marsh.	Upland-willow
Salix pyrifolia Anderss.	Balsam-willow
TYPHACEAE	CATTAILS
Typha latifolia L.	Broad-leaved cattail
Typha angustifolia L.	Narrow-leaved cattail
Typha glauca Godr.	Hybrid

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[a] nomenclature in Tables 6 and 7 follows Gleason and Cronquist 1963

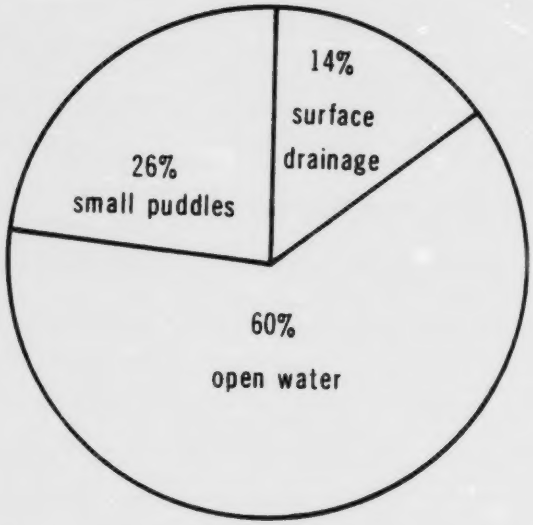


FIGURE 1 SURFACE WATER TYPES ON TAILINGS

The amount of vegetation cover provided by the indigenous species on the dry sections of the tailings sites has not yet been quantified. However, the contribution of indigenous vegetation from a visual evaluation of the sites for most revegetated sites is small, if not negligible. On tailings which have not been revegetated, mosses, trees and wetland species often constitute a relatively good vegetation cover.

All sites were evaluated for the completeness of their vegetation cover regardless of origin (indigenous or seeded). About 27% of all sites are completely covered by grasses, about 33% show small bare areas, and the remaining sites have larger bare areas of tailings (Figure 2). About 60% of all abandoned or inactive tailings sites investigated support a good vegetation cover.

About 54% of all the sites have a mixed cover of indigenous and seeded species (Figure 3). About 13% have been seeded but are not at all invaded by indigenous species. The remaining 33% (mainly the Bancroft sites and the tailings spills in Elliot Lake) are invaded by indigenous species alone.

If the occurrence of the species is viewed in relation to the revegetation practices used, some trends are indicated. Tailings sites with different amelioration methods and length of time since their initial amendments are compared for species richness in Table 8. The species richness of the Williams site, which was covered with top soil, is high and similar to that of the Bancroft sites. The Nordic site, the oldest of all

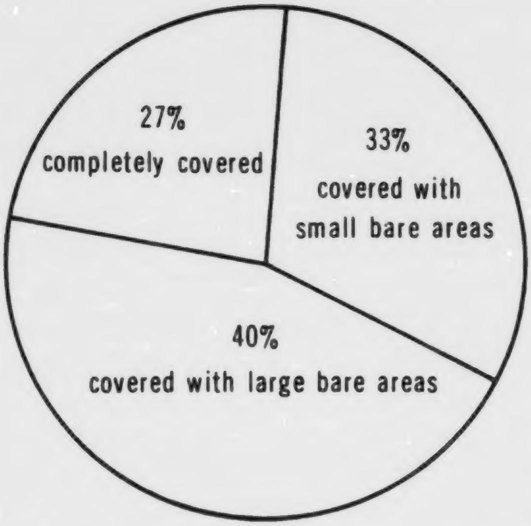


FIGURE 2 COMPLETENESS OF THE VEGETATION COVER

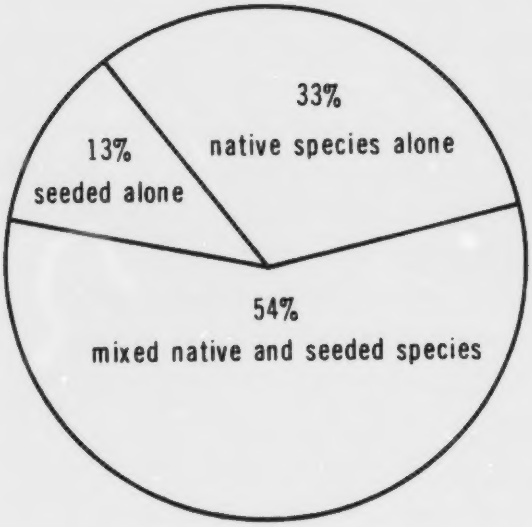


FIGURE 3 TAILINGS SITES WITH SEEDED AND NATIVE SPECIES

TABLE 8 SPECIES RICHNESS, TIME AND TYPE OF AMENDMENT

Years Since Amendment (as of 1980)	Type of Amendment and Site Name	Number of Introduced Species	Number of Natural Species	Total Number of Species
4	Gravel, topsoil, etc. (Williams)	4 - 5	30	34
10, 5, 2	Liming, grasscover (Nordic Main)	10	9	19
2	Liming only (Stanrock Main)	3	15	18
10	Liming, experimental mulching and seeding (Crotch)	9 - 7	18 - 16	25
23	None (Bicroft)	0	30	30
17	None (Auger Lake)	0	49	49

amended tailings, is invaded by fewer indigenous species than is Stanrock which received only lime for surface stabilization. It is noteworthy that the experimental plots (mulched and/or limed) on Crotch Lake have a high number of indigenous species.

3.2 Characteristics of Abandoned Uranium Mill Tailings Materials

To completely describe the elemental composition and properties of the surface (0-20 cm) of inactive uranium mill tailings sites would be an enormous task. However, the type of vegetation cover and its ability to survive is intimately connected to chemical and physical properties of the substrate which support it. It follows that information on the elemental composition and basic chemical characteristics of the tailings surfaces are essential parts of the study of long-term stability of these waste depositories.

The chemical aspects of uranium mill tailings presented in this section were analyzed with emphasis on the parameters which are likely to be of significance to a stable vegetation cover. However, it is important to note that the information gained from this survey may be indicative of some general trends. Confirmation of outlined trends is often necessary.

3.2.1 Concentration of Elements in Tailings. Mean ranges of concentrations of selected elements for individual sites and a mean concentration for the areas of Bancroft and Elliot Lake are presented in Table 9. The area mean is calculated based on the site means. The number of tailings sites with the number of samples analyzed from each site are given. It is difficult, if not impossible, to determine the nature of a representative tailings sample as tailings surfaces were shown to be quite heterogeneous. The means are derived from tailings samples from different collections on the sites (trees, sedges, cattails and bare tailings). It is rather surprising to find that some elements occur in average concentrations in areas with meaningful concentration ranges for the sites. The values obtained by neutron activation analyses are related to the matrix of the material; comments on the analytical errors, therefore, give a perspective on the absolute values (Table 9).

The concentrations of the elements Mn, Mg, Na and Cl in the inactive uranium mill tailings differ drastically between the Bancroft and the Elliot Lake areas. Aluminum concentrations determined in the soils from both areas are of interest since the samples were collected from locations which supported the same species of plants. The tailings samples from the Elliot Lake sites generally have lower concentrations than do the soils. The Bancroft sites, however, are generally higher in all elemental concentrations encountered. Aluminum concentrations are again an exception for both areas. The aluminum concentrations of the tailings are within the standard deviation of the soil concentrations. For the element chlorine, some individual sites may have concentrations in the ranges of those determined for soils, but they generally follow the same trend. Statistical analyses of these observations are clearly warranted.

Contrary to the elements discussed in Table 9, the concentrations of calcium and uranium (Figures 4 and 5) determined during this survey show tremendous variation and cannot be used to characterize tailings sites or the tailings materials. The concentration of calcium within one site may vary by as much as two standard deviations, and the standard deviation in nearly all cases exceeds the mean concentration. In Elliot Lake, many samples (approximately 50% of all tailings samples collected) have calcium concentrations below the detection limit ($\geq$600 μg/g); these were excluded from calculations for Figure 4. Thus, the local variations of calcium concentrations on the tailings sites is even larger than shown. Tailings samples with low concentrations of calcium are important. The calcium concentrations in the soil appear to vary less,

TABLE 9 CONCENTRATIONS OF Mn, Mg, Na, Al AND Cl IN URANIUM MILL TAILINGS FOR BANCROFT AND ELLIOT LAKE

Element	Location	Number of		Concentration (μg/g)			Analytical Comments
		Sites	Samples	Range	Area Mean	Standard Deviation of Mean	
Mn	Bancroft	5	57	360 - 1 190	840	300	Error: 0.5-5% Low values: 10-15% Detection limit: 20-250 μg/g
	Elliot Lake	14	92	10 - 180	50	60	
	Soils*	10	29	80 - 780	400	230	
Mg	Bancroft	5	57	8 570 - 11 060	13 400	7 700	16% Al corrected on mean of site Error: 2-10% Detection limit: 30-220 μg/g
	Elliot Lake	9	70	1 240 - 8 780	3 800	2 200	
	Soils*	10	31	2 250 - 17 000	8 250	4 300	
Na	Bancroft	5	53	25 900 - 37 400	29 600	4 500	Error: 0.6-1% Detection limit: 85-330 μg/g
	Elliot Lake	12	83	360 - 2 100	870	570	
	Soils*	10	31	800 - 27 100	16 850	6 040	
Al	Bancroft	5	57	48 300 - 54 700	54 200	6 600	Error: 1-2% Detection limit: 20-34 μg/g
	Elliot Lake	13	92	19 000 - 43 500	30 700	10 160	
	Soils*	10	31	11 000 - 63 300	44 030	15 600	
Cl	Bancroft	5	53	440 - 590	540	60	Error: 4-25% Detection limit: 15-130 μg/g
	Elliot Lake	13	80	70 - 290	170	85	
	Soils*	6	23	240 - 480	350	86	

* number of locations sampled in the Bancroft and Elliot Lake areas

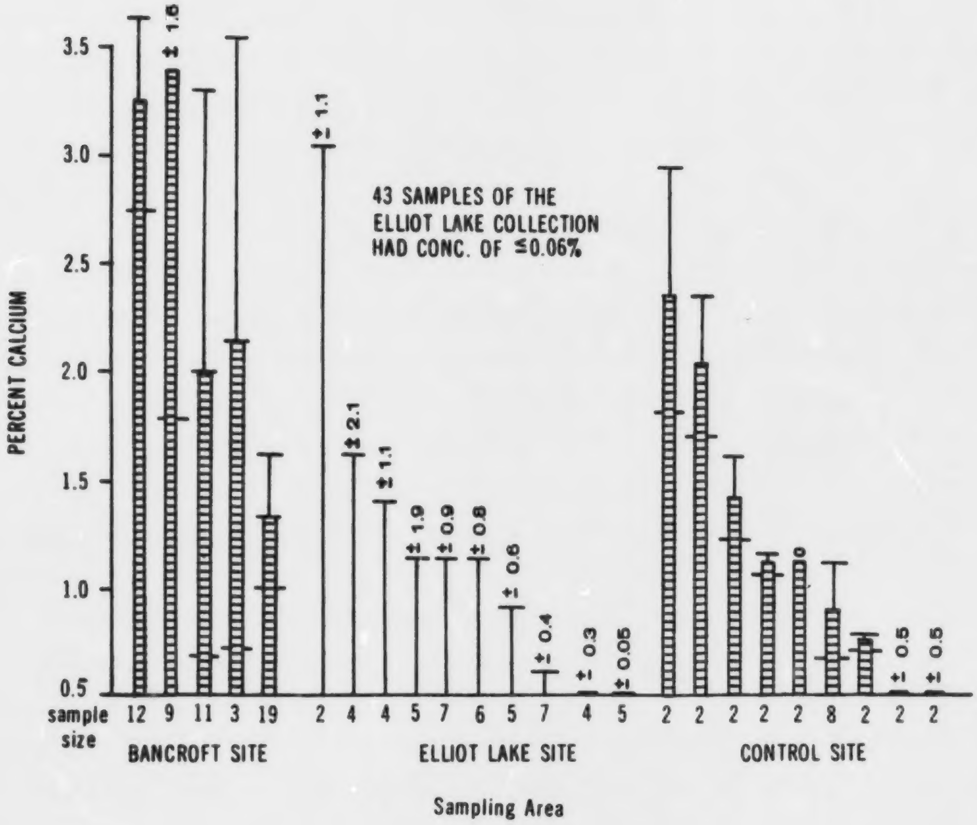


FIGURE 4 CALCIUM CONCENTRATIONS IN URANIUM MILL TAILINGS SITES (Standard deviations are given for each site.)

particularly since the means are based on only two samples per vegetation collection. Considering that all soil samples collected have a mean calcium concentration of 1.2% (±0.68%), it is representative of the calcium concentration encountered by the vegetation in the vicinity of the Bancroft and Elliot Lake tailings. In general, the absence of calcium is evident on the tailings in the Elliot Lake area; however, there is also a high local variation in calcium concentrations within the sites.

The uranium concentrations determined in the tailings are more regular than those of calcium (Figure 5). The average uranium concentration in both areas appears to range from 10 to 50 μg/g. Three of the tailings sites and three locations where soil was collected are higher. In the soil, the uranium content approaches 0.1% at one location. Uranium concentrations in the tailings material appear site-specific and not related to the area or the ore body. Again, a statistical treatment will be necessary to confirm these preliminary observations.

The elements discussed up to this point were determined in absolute concentrations. The method used (neutron activation analysis) also yielded information about elements present at or below their detection limits. The concentrations at the detection limits are available for dysprosium, barium, titanium, strontium, iodine, bromine and vanadium. The information collected will be used outside this survey. None of these elements appears to be present in environmentally significant concentrations.

In this survey, neutron activation analysis was utilized as a screening method, not only to determine the elemental compositions of the tailings, but also to identify problems such as elevated concentrations of potentially toxic elements on the tailings sites. The usefulness of the screening process is indicated by the results for elemental concentrations of arsenic (Table 10). For the determinations of arsenic concentrations, several samples were selected from each of the tailings locations under investigation. Two tailings deposits which originated from the same milling operation were found to have considerably elevated arsenic levels (Sites X and W). Nearly all other tailings samples yielded concentrations below 40 μg/g. These results obtained for arsenic indicate that site-specific problems can occur for certain elements.

Heavy metal concentrations in tailings are summarized in Table 11. Nickel is the only element which has similar concentration ranges in the tailings for both areas. Copper, cobalt and lead appear to be present in generally higher concentrations in the tailings of the Elliot Lake area. However, the standard deviations indicate that large ranges of concentrations are encountered. An analysis of the data on a site-specific basis

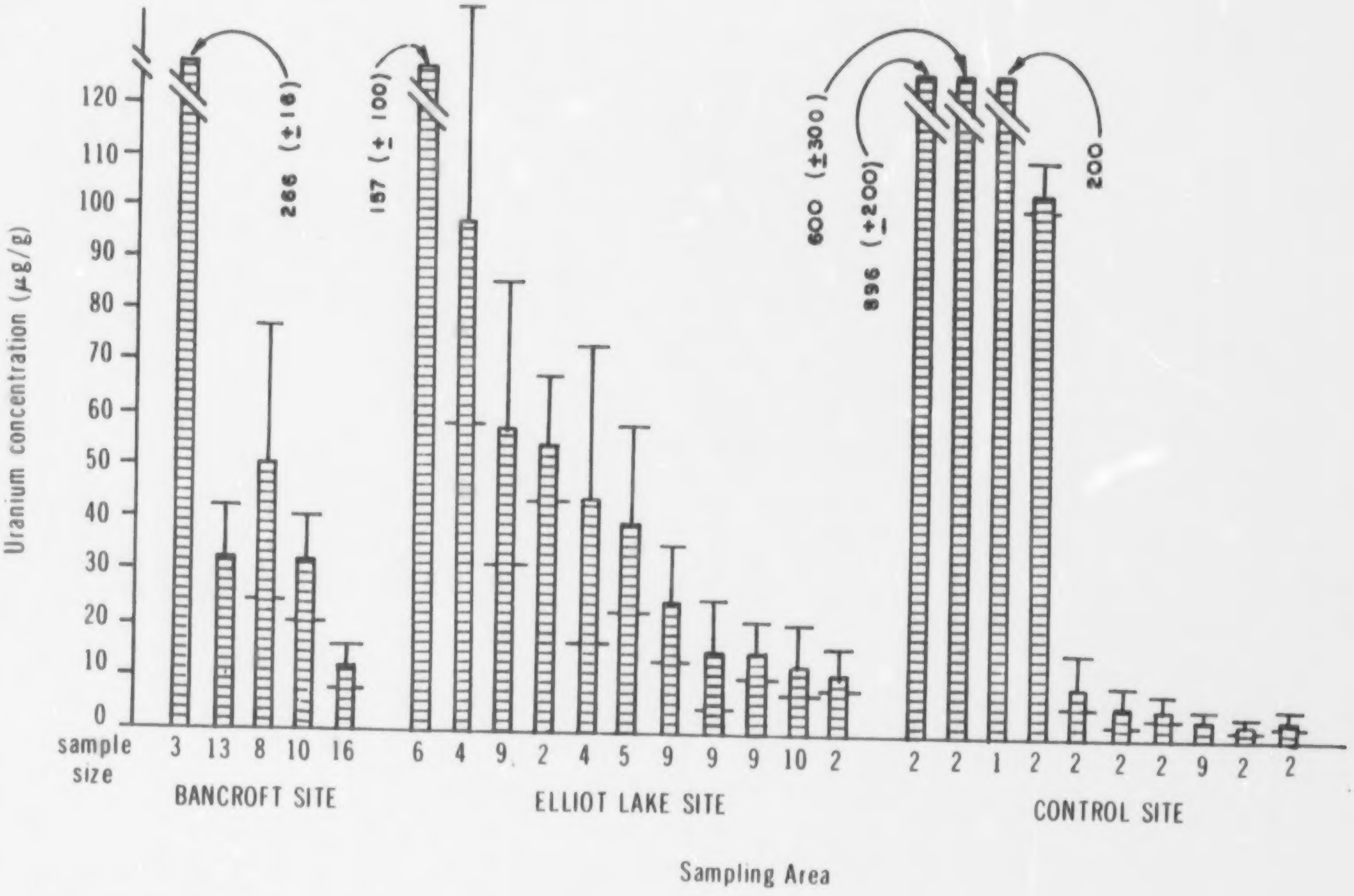


FIGURE 5 URANIUM CONCENTRATIONS IN URANIUM MILL TAILINGS SITES
(Standard deviations are given for each site.)

TABLE 10 ARSENIC CONCENTRATIONS IN URANIUM MILL TAILINGS

Location	Number of Samples Irradiated (total)	Detection Limit (µg/g)	Number of Samples Above Detection Limit	Concentration (µg/g)	Analytical Error (%)
Bancroft	22	40	2	42	28
			Site A: (2 out of 6 samples)	66	14
Elliot Lake	28	none*	21	10 - 63	14 - 13
			Site X & W: 7	380 - 1 125	1
Soils	9	28	2	40	17
				23	16

* Na concentrations in Elliot Lake tailings are considerably lower than in Bancroft. The reduced detection limit in the Elliot Lake samples is an expression of the matrix effects.

is necessary. The high variation in heavy metal concentrations indicates that in assessing the transport of metals from the tailings to the vegetation, only the materials immediately surrounding the roots of the plants should be considered.

A comparison of elemental concentrations in tailings and soils can be of some ecological importance (Table 12). To facilitate such a comparison, literature values for soils of all the elements discussed in this section are summarized in Table 12. However, such a comparison has to be interpreted cautiously since, as later emphasized, tailings are not necessarily comparable to soils. Furthermore, elemental concentrations do not reflect availability to biota, and availability is likely to differ between soils and tailings. Other characteristics such as pH, conductivity, organic matter and moisture content are also important factors influencing elemental transport and plant development. These characteristics of tailings are discussed in the next section.

The average elemental concentrations in tailings compared to those in soils are presented as an overview in Table 13. Essentially, concentration ranges of aluminum, magnesium and nickel were similar in tailings and soils for both mining areas. The differences between the tailings materials were based on average elemental concentrations. A depletion of manganese and sodium in the Elliot Lake tailings is apparent.

Chlorine is slightly enriched for the tailings in Bancroft, when compared to soil and the literature concentrations. Generally, lead appears to be enriched within the tailings material in both areas. The high concentrations of copper and cobalt in the Elliot Lake tailings are of little importance in this type of comparison since their standard deviations are extremely high (Table 11). In some locations, copper and lead concentrations were found to be relatively higher in soils than in tailings. Such differences can be expected since the literature values are for mineral soils, and higher concentrations of metals often occur in humus-rich soils. In general, the soil concentrations determined in this survey are within the elemental concentration ranges given in the literature (Table 12).

TABLE 11 METAL CONCENTRATIONS IN URANIUM MILL TAILINGS

Element		Bancroft	Elliot Lake	Both areas
Cu	$\bar{x}$	30	116	85
	sd	16	226	185
	n	52	90	142
Ni	$\bar{x}$	13	15	14
	sd	16	17	17
	n	51	91	142
Co	$\bar{x}$	5.8	79	52
	sd	5.3	165	135
	n	51	85	136
Pb	$\bar{x}$	123	266	189
	sd	105	233	202
	n	51	90	141

$\bar{x}$ mean (μg/g)
sd standard deviation (μg/g)
n number of samples

TABLE 12 AVERAGE ELEMENTAL CONCENTRATIONS FOR SOILS

Element	Bowen (1966) (µg/g)	Allen et al. (1974)* (µg/g)	Soils from the Elliot Lake and Bancroft area (µg/g)
As	6	1 - 10	<8 - 40
Al	71 000	1 000 - 150 000	44 000 ± 15 600
Ca	13 700 (7 000 - 500 000)	5 000 - 20 000	12 000 ± 6 800
Cl	100	50 - 500	350 ± 86
Cu	20 (2-100)	5 - 100	12 - 317
Co	8	1 - 60	5 - 45
Mg	5 000	2 000 - 30 000	8 250 ± 4 300
Mn	850	200 - 3 000	400 ± 230
Na	6 300	1 000 - 10 000	16 850 ± 6 040
Ni	40	5 - 500	nd - 63
Pb	10	2 - 20	7 - 430
U	1	not given	3 - 900

* Ranges for mineral soil values generally encountered.
nd = not detected

TABLE 13 COMPARISONS OF AVERAGE ELEMENTAL CONCENTRATIONS IN TAILINGS TO AVERAGE SOILS CONCENTRATIONS

Elements (compared to Table 11 values)	Bancroft			Elliot Lake		
	Higher	Same	Lower	Higher	Same	Lower
As		N/A			N/A	
Al		X			X	
Ca		N/A			N/A	
Cl	X				X	
Cu		X		X		
Co		X		X		
Mg		X			X	
Mn		X				X
Na	X					X
Ni		X			X	
Pb	X			X		

N/A = not applicable

3.2.2 Chemical Characteristics of Tailings. The elemental composition of uranium mill tailings described in the previous section forms only one aspect of environmental conditions for biota on waste material. The interaction of water with tailings will determine other ecologically important characteristics of waste material. Some of these parameters have been determined in this survey, and their statistics are summarized in Table 14.

A comparison between tailings material and soil is facilitated by presenting mean values and their statistics for pH, conductivity, loss-on-ignition, and percent moisture loss. These parameters are often not normally distributed for tailings as indicated by the values of skewness and kurtosis. The mean values of these parameters are given separately for Bancroft and Elliot Lake in addition to a combined value. It is evident that the differences between tailings material and soil characteristics are drastic. The noted differences of tailings between mining areas are comparatively small. This is further emphasized by the differences in the distribution of the characteristics. Subsequently, the comparisons of the mean values of the characteristics discussed are only of value in a very general context.

TABLE 14 pH, CONDUCTIVITY, LOI AND PERCENTAGE MOISTURE LOSS OF TAILINGS AND SOILS

Site		pH			Conductivity (µmhos/cm)			Loss-on-ignition			Percentage Moisture Loss		
		A	B	E	A	B	E	A	B	E	A	B	E
Number of Samples	t	100	32	68	52	25	27	72	22	50	57	17	40
	s	21	5	16	10	5	5	-	-	17	-	-	9
Mean Values	t	4.50	4.35	4.58	1 076	808	1 324	2.7	1.21	3.4	20.6	15.5	22.8
	s	5.40	4.90	5.61	274	66	482	-	-	22	-	-	30
Standard Deviation	t	1.2	1.0	1.3	993	1 144	770	3.8	1.7	4.3	13	7.9	13.7
	s	0.8	0.7	0.8	230	26	106	0	-	19	-	-	24
Maximum	t	7.3	6.2	7.3	5 000	5 000	2 600	20	8	20	68	29	68
	s	7.2	6.0	7.2	600	110	600	-	-	76	-	-	71
Minimum	t	1.4	1.4	2.5	16.0	16.0	180	0.1	0.1	0.2	1.2	7.7	1.2
	s	4.4	4.4	4.7	40	40	310	-	-	2.2	-	-	5.4
Skewness	t	0.26	-0.84	0.43	1.33	2.28	0.24	3.16	3.07	2.79	1.16	0.66	0.96
	s	1.0	1.74	1.18	0.26	1.46	-1.17	-	-	1.52	-	-	0.6
Kurtosis	t	-0.48	0.89	-0.99	3.07	6.6	-1.48	10.79	10.85	7.79	2.62	-1.49	2.09
	s	0.42	3.25	0.27	-2.09	2.9	2.45	-	-	2.57	-	-	-1.25

t = tailings
s = soil
A = both areas
B = Bancroft
E = Elliot Lake

Low pH values appear to be characteristic of the tailings in general. The mean pH value is given as the arithmetic mean of all measurements made on the tailings and the soils; it is thus not a mean of the hydrogen ion activity. The mean pH of the Bancroft tailings is very similar to that of the Elliot Lake tailings.

The conductivity of the tailings slurries differs drastically from that of the soils and has a large range of values. A relationship between pH and conductivity can be expected. In Figure 6, an attempt is made to correlate all the pH and conductivity measurements obtained in the field and in the laboratory. The soils seem to be separated clearly from the tailings. For the soils at a pH above 4, the conductivity is about 500 µmhos/cm. Two clusters of values are indicated within the tailings samples; conductivity of one cluster is around 1 000 µmhos/cm, and of a second cluster around 2 000 µmhos/cm. Further work is required to identify the areas of low or high conductivity on the tailings pond.

The organic matter expressed as loss-on-ignition (LOI) is low in tailings; the distribution is very narrow and shifted to the left of the mean. The maximum values of 8 and 20% for some samples of Bancroft and Elliot Lake tailings are likely a result of the sorting techniques, where some organic detritus was accidentially left in the samples. In essence, the amount of organic material accumulated around the vegetation growing on the tailings is very small.

Moisture loss is a determination of a relatively limited value, due to its dependence on weather conditions and sampling methods; however, some observations are possible. Forty percent of the tailings samples were collected from the root regions of cattails, sedges and trees. It appears that generally the root region of the vegetation of the tailings has a reduced moisture content.

3.2.3 Tailings Interactions with Vegetation. Most of the samples of the tailings analyzed in this survey were closely associated with vegetation samples; they were collected from 0 to 5 cm depth around the excavated plant or at a depth of 15 to 20 cm in the root region. The enormous range of the parameters given in Table 14 indicated that the vegetation growing on the tailings has the ability to deal with these conditions. It is of interest to delineate the conditions further.

Moisture content and organic matter are correlated as shown in Figure 7. The soils collected with the trees appear to increase in organic matter as the moisture content

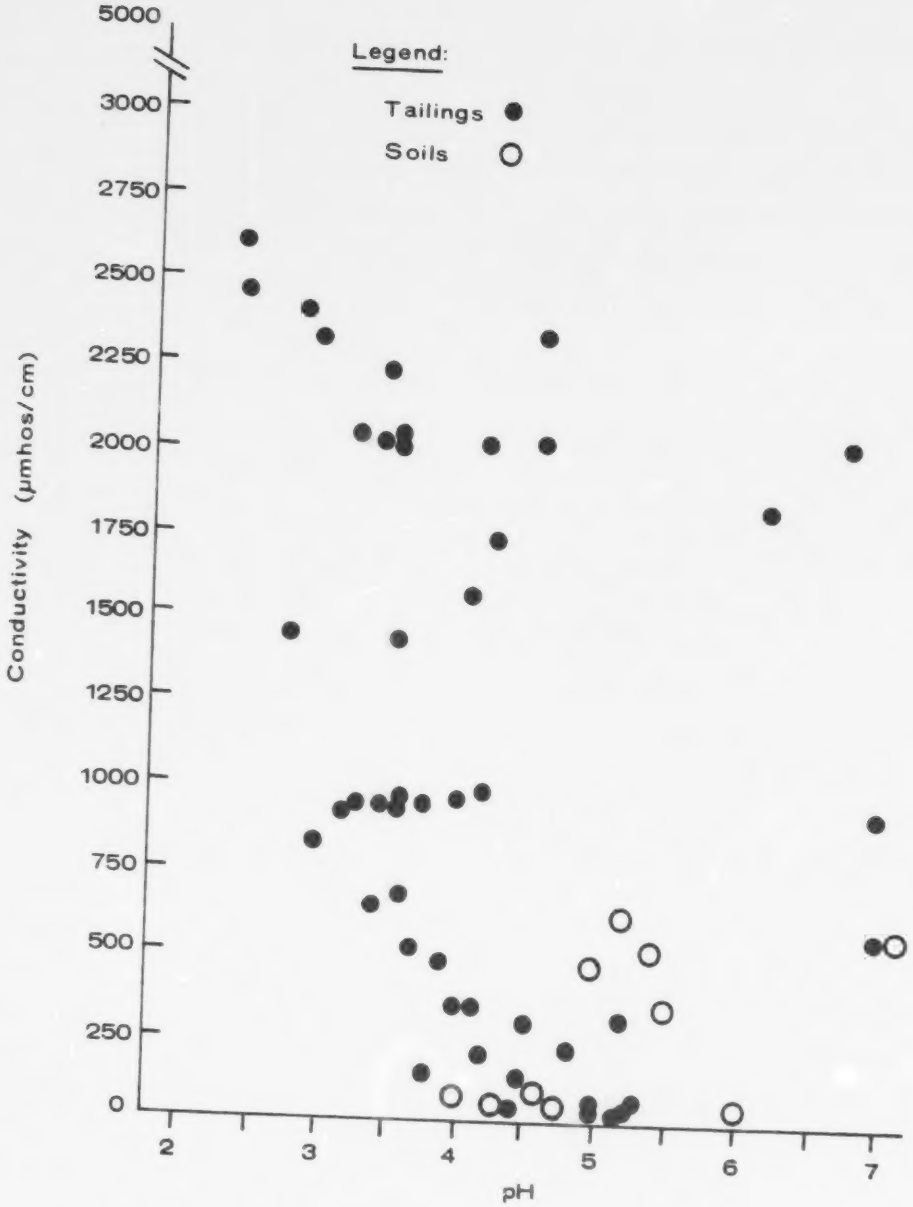


FIGURE 6 THE pH AND CONDUCTIVITY IN TAILINGS AND SOIL SLURRIES

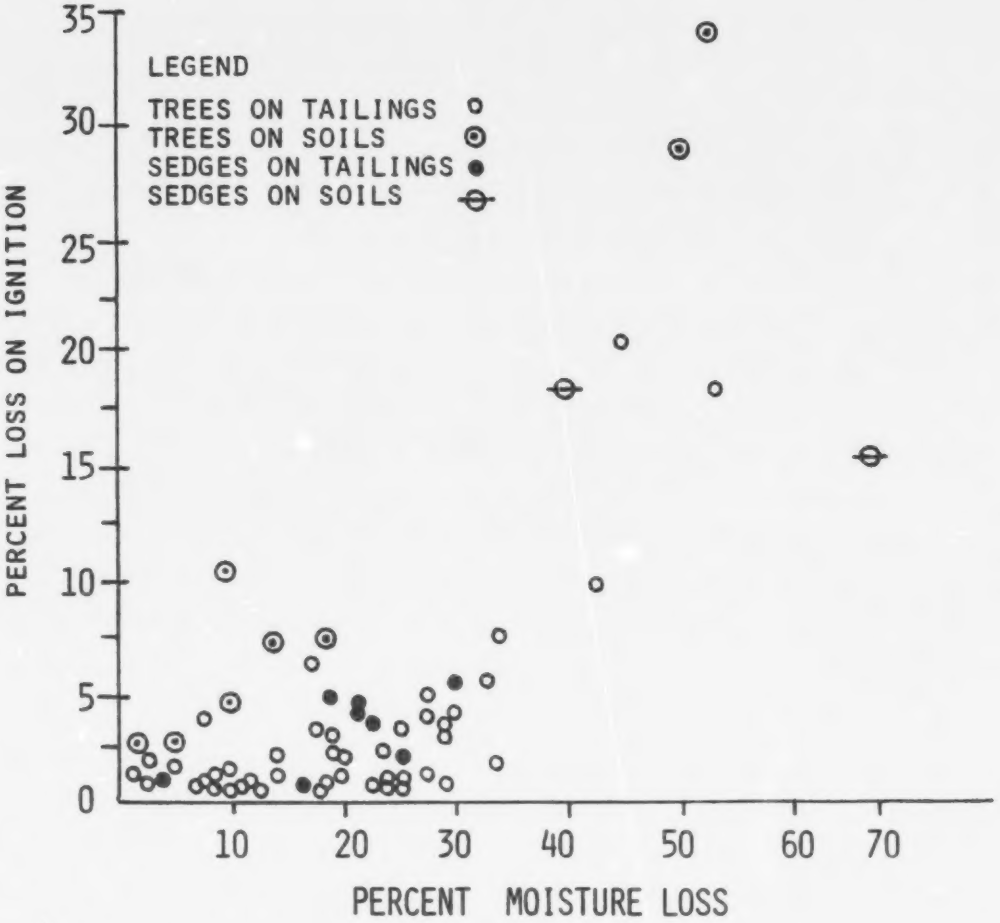


FIGURE 7 RELATIONSHIP BETWEEN MOISTURE LOSS AND ORGANIC MATTER

increases. Most of the tailings samples fall within the lower portion of this relationship (5% loss-on-ignition and 30% moisture loss). However, some exhibit a similar trend to that of the soils. Clearly, more determinations are needed to substantiate these observations.

In order to determine some interactions of the vegetation with the tailings, pH determinations on the root region of the plants were carried out in the field and later in the laboratory (Figure 8). Changes in the pH values can be noted between the field determinations and laboratory determinations for tailings collected from areas free of vegetation. These pH values obtained in the field agree reasonably well with those of a distilled water slurry (1:1) prepared in the laboratory. For tailings samples which were associated with cattails, a striking decrease in pH can generally be noted for the same comparisons. These changes in the pH values are more dramatic for the neutral values than for the acidic values determined in the field.

In order to support the observations in Figure 8, the pH values of the surface samples (0-5 cm) were compared to those of the root region (20-25 cm) in the laboratory (Figure 9). The differences in pH values of bare tailings (free of vegetation) between the surface and the deep samples are small, and the direction of change is irregular. For most samples associated with cattails, the surface tailings material has a lower pH value than that of the root region. A similar trend occurs for the samples associated with the sedges; however, only half of the samples show the same direction of change in the pH values. The tailings material sampled with both tree species are indicative of a reverse trend. The surface layer was less acidic than the root region in nearly all cases. The differences are greater in some locations than in others; nevertheless, the change is at least 0.5 of a pH unit. The number of observations available to illustrate the interaction of vegetation within the tailings is limited, but the observed pH changes warrant further investigation.

3.3 Heavy Metals and Radionuclides in Vegetation Growing on Tailings

In the survey of inactive uranium mill tailings, trees and wetland plants were identified as important vegetation groups. Some species from this group were selected to determine heavy metal and radionuclide uptake from the tailings material. The main objective was to delineate concentration ranges encountered as a result of the transport of hazardous elements from the tailings to biota.

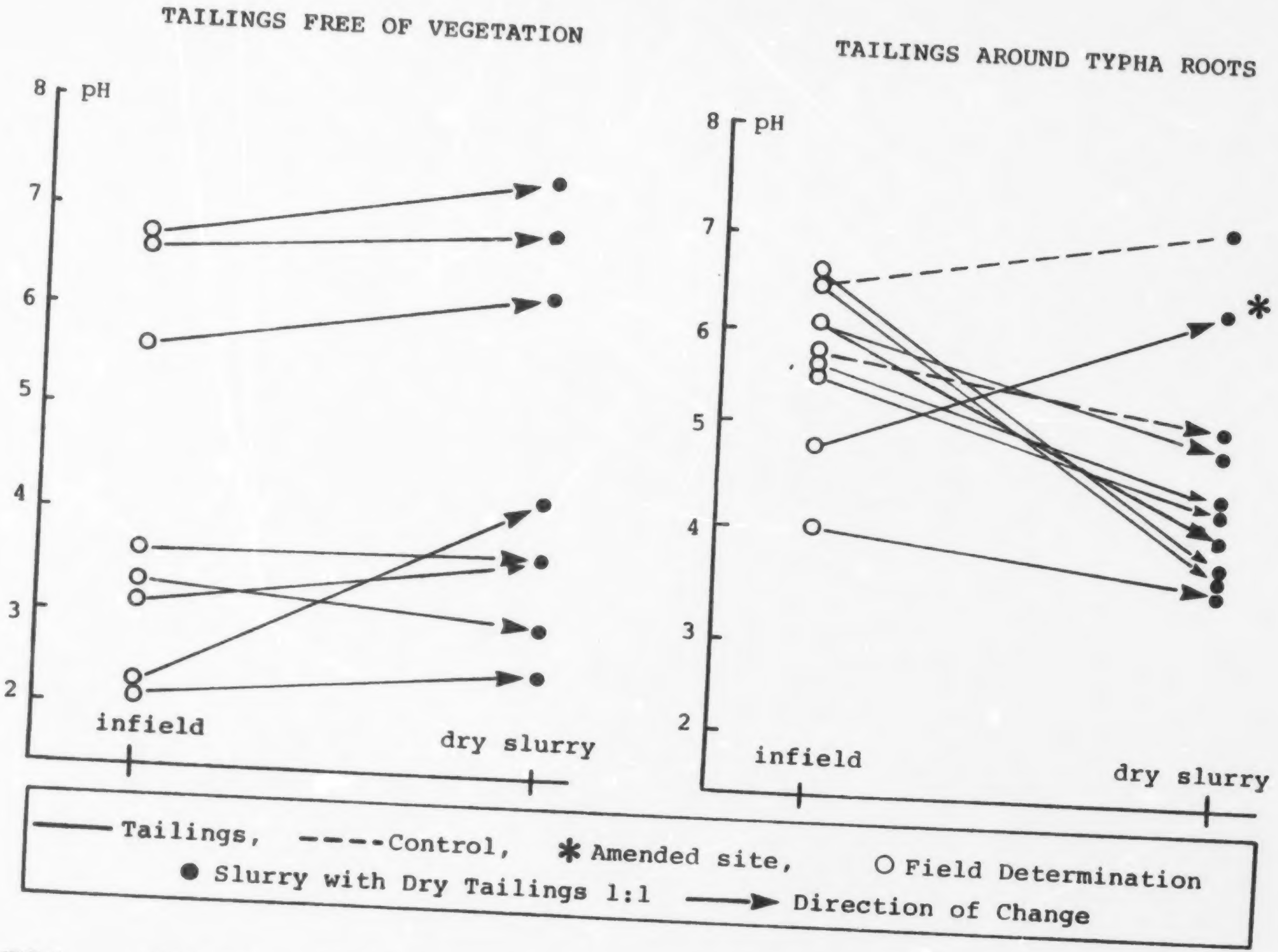


FIGURE 8 CHANGES OF pH IN TAILINGS SLURRIES AFTER REMOVAL OF PLANTS

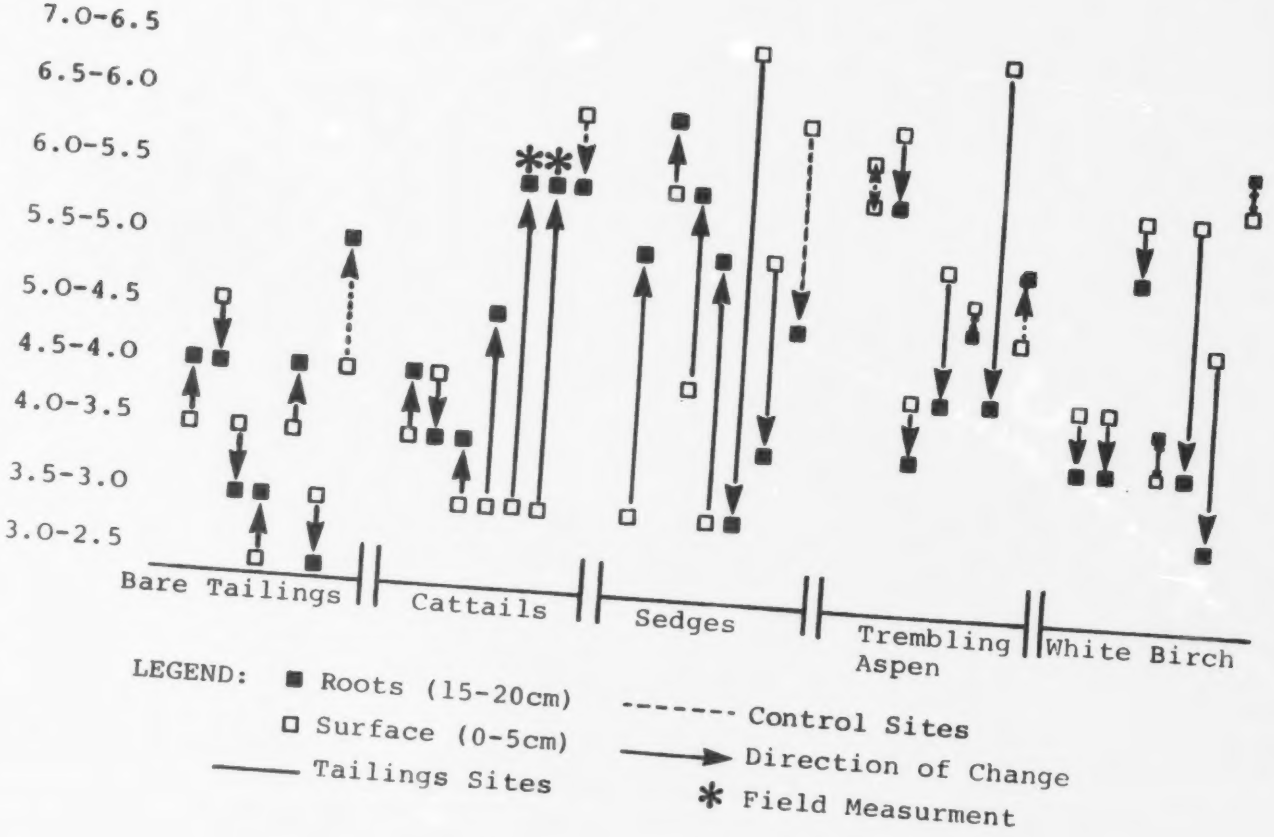


FIGURE 9 DIFFERENCES IN pH OF TAILINGS AND SOILS AT THE SURFACE AND IN THE ROOT REGION

As documented in the previous sections, tree establishment on most tailings sites has taken place only in certain areas. Tree specimens collected for analyses were at least half a metre in height and were growing on what appeared to be tailings material. The scarcity of the trees on some tailings sites severely limited the choice of specimens. It was possible to locate on nearly every site one suitable specimen of white birch and one of trembling aspen. In total, 20 trees were located for analyses (Table 15). The trees, the oldest of which was 7 years old, had a mean height of 85 cm and a mean shadow diameter of 36 cm. Trees of similar height and growth on soil were generally 2-4 years old. Tree heights and ages are compared in Figure 10. Although the number of trees for each age group were limited, it appears that height on tailings was slightly less than on control sites. Further investigation is necessary.

The nature of the surface in an area of 1 m^2 around the tree is documented in Table 15. In general, the surface of most locations was neutral to slightly acidic, with the organic matter content of the surface frequently reflecting the description of the quadrat. Organic matter on these surfaces is an expression of the litter accumulation around the trees; this in turn is related to the presence of additional vegetation.

3.3.1 Metal Concentrations in *Populus tremuloides* and *Betula papyrifera*. In the previous section, heavy metal concentrations in the tailings were found to vary from one tailings site to another, and from one sampling location to another. Before an evaluation of heavy metal concentrations in trees is pursued, a comparison of metal concentrations in the trees between the collection areas is warranted. The results for both tree species collected from Bancroft, Elliot Lake and control areas are summarized in Table 16.

Concentrations of copper and lead appear to be slightly higher in both tree species from the Elliot Lake area than in those from the Bancroft area. Also, concentrations of these two metals in trembling aspens may be higher on tailings sites than on control sites which is not the case for white birches. Nickel and cobalt frequently were not detectable in some organs of the trees; organs which had detectable concentrations are indicated in the footnotes of Table 16. The concentrations of heavy metals in trees are too variable to substantiate any differences between the tailings areas and the control sites. The concentrations of copper and nickel in the trees on both tailings and control sites are close to concentrations given for land plants by Bowen (1966) (see footnote 1 in Table 16). The concentrations of lead and cobalt are higher than those given by Bowen (1966). Further analyses may clarify the varied impression gained from an evaluation of Table 16. However, it appears unlikely that significant differences exist in metal concentrations in trees between the areas.

TABLE 15 TREE SIZES AND CHARACTERISTICS OF THE COLLECTION SITE

Sample Code	Age (yrs)	Height (cm)	Diameter Shadow (cm)	Surface (pH)	Tailings Surface LOI (%)	Associated Plants in 1 m^2 Around the Tree
Bancroft						
A - WB	4	56	25	5.5	0.80	willow, sedges, mushrooms
- TA	6	75	40	5.5	0.80	moss cover, 50% bare
C - WB	4	45	30	4.5	1.00	two sedges
- TA	4	80	20	4.1	0.66	bare tailings
D - WB	5	105	45	5.3	1.24	bare tailings
- TA	5	90	28	5.3	1.24	bare tailings
G - WB	4	75	45	5.0	0.42	growing out of buried log 100% moss cover
- TA	7	65	25	5.1	0.56	moss cover, strawberries
Elliot Lake						
H2 - WB	-	83	30	5.9	3.41	pin cherry, 100% grass cover, raspberries
- TA	-	100	30	5.6	1.59	yellow clover, sedge, 100% grass cover
PN - WB	5	112	75	6.0	3.85	moss growing out of dead wood
Q - WB	-	67	25	5.6	9.22	two maple seedlings, balsam fir, moss cover
S - WB	4	86	60	4.7	1.88	willow, moss cover
- TA	-	100	55	6.2	3.03	willow, moss cover
T - WB	-	65	45	4.3	1.94	sedges, bare tailings
VME - WB	-	85	47	7.0	0.94	70% grass cover, bare clover
- TA	-	65	67	7.3	1.09	70% grass cover, bare clover
X - WB	-	105	35	6.7	7.16	sedges, willow and grass
- TA	-	88	27	6.7	5.01	sedges, willow and grass
Y - WB	-	85	40	2.9	7.78	maple seedlings growing out of dead wood
Control Sites						
C1 - WB	2	90	47	5.2	6.94	golden rod, sandy, moss cover, pin cherry
- TA	3	120	70	4.7	10.65	
C2 - WB	-	110	37	6.9	29.79	golden rod, strawberry moss, perly everlasting
- TA	4	135	40	6.9	29.79	
C3 - WB	3	80	40	5.5	2.18	moss cover, rocks
- TA	-	135	45	5.5	2.18	

Letters A to Z are site codes
WB - white birch
TA - trembling aspen

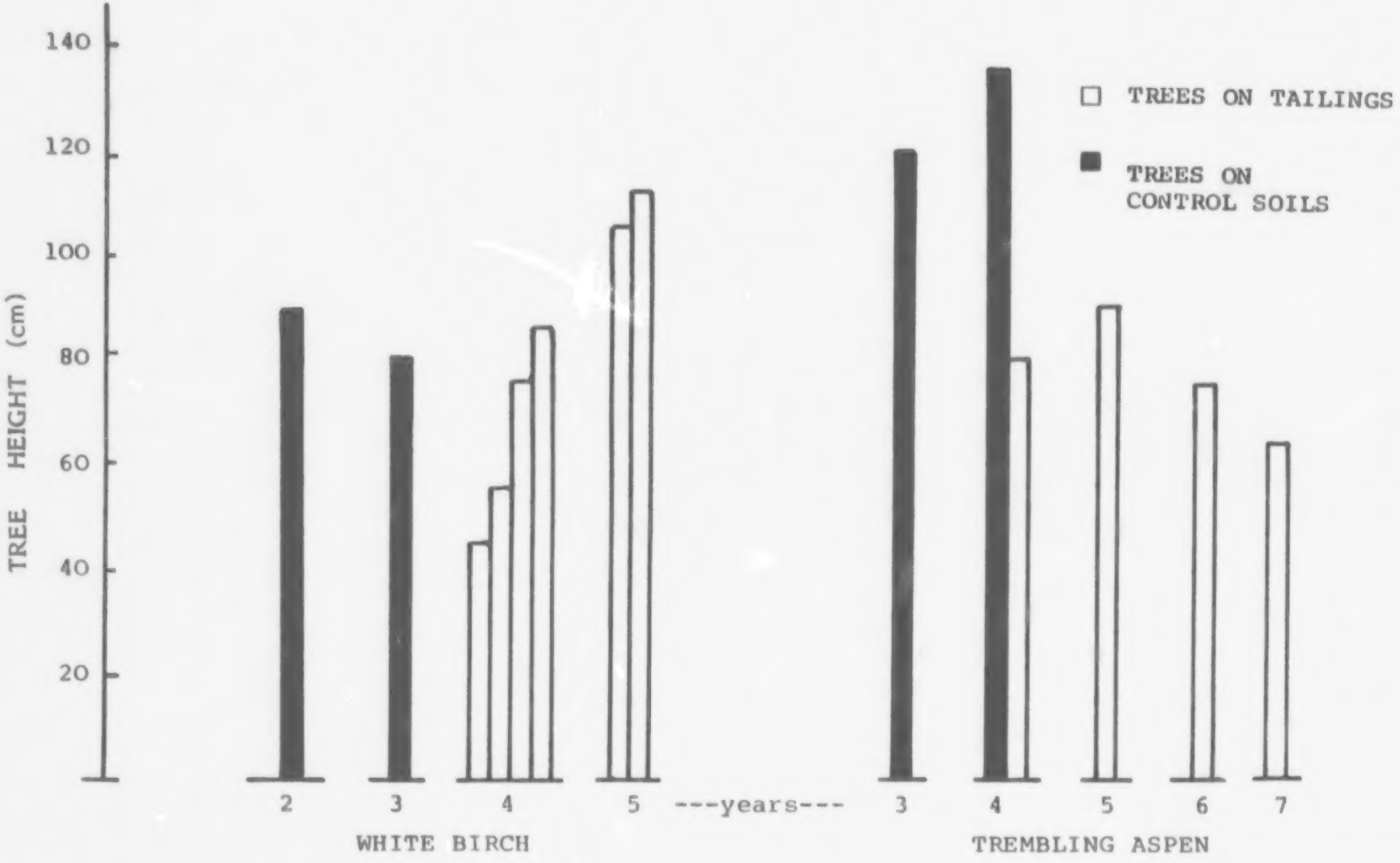


FIGURE 10 HEIGHT AND AGE OF TREES ON TAILINGS AND CONTROL LOCATIONS

TABLE 16 MEAN METAL CONCENTRATIONS IN TREES GROWING ON TAILINGS OR SOILS IN BANCROFT AND ELLIOT LAKE[a]

Number of Tailings Sites and Location		Trembling Aspen[b]				White Birch[b]			
		Cu	Ni	Pb	Co	Cu	Ni	Pb	Co
		(µg/g dry weight)				(µg/g dry weight)			
Bancroft	$\bar{x}$	13.2	7.2	9.7	3.2[c]	11.3	5.2[d]	21.6	3.8[d]
4 tailings	sd	3.4	3.8	5.7	2.2	7.5	3.3	23.7	1.8
sites	n	12	4	9	3	12	9	12	4
Elliot Lake	$\bar{x}$	15.0	5.4	13.8[e]	4.9[e]	9.2	4.8	27.8	2.7
8 tailings	sd	10.1	2.6	15.5	4.0	3.8	2.3	33.3	1.4
sites	n	12	11	6	8	24	16	19	15
Control	$\bar{x}$	8.8	3.9	7.3	1.9	8.7	5.3	45.3	1.9
6 locations	sd	4.0	2.8	1.0	3.2	3.2	2.3	53.2	0.9
	n	9	6	3	5	9	7	6	6

Legend: $\bar{x}$ = mean
sd = standard deviation
n = number of samples

a Bowen (1966) land plants: Cu, 14 ppm; Ni, 3ppm; Co, 0.5 ppm; and Pb, 2.7 ppm.

b total number of trees:

	Trembling Aspen	White Birch
Bancroft	4	4
Elliot Lake	4	8
Control	3	3

c leaves only and not detected in roots or stems

d leaves and roots rarely detected in stems

e only three (3) specimens had detectable concentrations mostly in leaves and roots

Based on the assumption that there are no major differences in metal concentrations between the trees growing in different locations, mean metal concentrations in different plant organs for each plant species are reported in Table 17. The leaves and stems of trembling aspen have consistent and comparable concentrations of copper but less consistent, although comparable, concentrations of lead. For both heavy metals, the roots have the highest concentrations, but also the largest standard error. Nickel concentrations appear to be higher in the leaves, with lower concentrations in both roots and stems. The cobalt concentrations in trembling aspen are varied in all organs.

In the white birch, copper is uniformly distributed throughout the tree, while the lead concentrations are extremely varied in all organs with standard errors larger than the mean concentrations. In both species of trees, nickel concentrations were highest in the leaves. However, the distribution of cobalt in different organs is similar for both species.

Both copper and lead were compared further on a site-specific basis. Mean concentrations of copper and lead in individual trees were calculated and given for each tree species along with the concentrations determined in the tailings or the soil collected with the specimens (Tables 18 and 19). A concentration factor was determined as the ratio of the mean tree concentration to that of the tailings or soil concentration.

The concentration factors for copper indicate that the concentration of copper in the trees is more or less a reflection of the concentrations of the growth substrate. Both species growing on the tailings or on soils in Elliot Lake and Bancroft appear to transfer copper in similar ratios. This indicates that there are no differences in uptake between the tailings areas or between growth substrates as shown in Table 18.

Lead concentration factors are generally lower in the Elliot Lake area than in the Bancroft area, or the control sites. The ratios of sites H and T in the Elliot Lake area are noteworthy: Site H was amended with top soil, which is reflected in the low lead concentration of the material around the roots. However, the concentration factor of this tree is similar to the trees on the Bancroft area or the control sites. The white birch collected on Site T had concentrations of lead as high as the trees on the control Site 2 which has the highest concentration factor of the entire tree collection (Table 19). The lower ratios of lead in trees of the Elliot Lake tailings cannot be considered a function of the tailings areas, but are rather related to functions of other parameters not determined

TABLE 17 MEAN METAL CONCENTRATIONS IN LEAVES, STEMS AND ROOTS OF TREES

Metals		Leaves		Stems		Roots	
		TA	WB	TA	WB	TA	WB
Cu	$\bar{x}$	11	10	12	6	16	12
	sd	3	4	3	2	11	6
	n	11	15	11	15	11	15
Ni	$\bar{x}$	6	6	2	2	3	3
	sd	3	3	3	2	3	3
	n	11	15	11	15	11	15
Co	$\bar{x}$	4	2	0.5	0.5	1	2
	sd	4	2	1	3	1	2
	n	11	15	11	15	11	15
Pb	$\bar{x}$	3	12	3	26	8	33
	sd	3	16	5	37	9	40
	n	11	15	11	15	11	15

Legend: $\bar{x}$ = mean is based on specimens which had detectable concentrations in all organs (µg/g)
sd = standard deviation (µg/g)
n = number of samples
TA = trembling aspen
WB = white birch

here. It is clearly necessary to make a more detailed analysis for the metal concentrations in trees.

3.3.2 Metals in *Typha latifolia*. Wetland communities are prominent features of inactive tailings sites. Therefore, transport of elements from the tailings to these biota is of interest. The sample collection of wetland communities dominated by *Typha* was interpreted in more detail than the tree collection. For example, the distributions of copper, nickel and lead concentrations in tailings and soils for surface and root region samples are analyzed (Figure 11). No major differences are apparent between the surface

TABLE 18 COPPER CONCENTRATIONS IN TREES GROWING ON TAILINGS, AND CONCENTRATION FACTORS.

Site Codes	Tailings concentration (μg/g)		Mean Concentration All Parts (μg/g)		Concentration Factors*	
	TA	WB	TA	WB	TA	WB
Bancroft						
A1	20**		10	7	0.5	0.3
C	23	37	17	18	0.5	0.8
D2	21		12	8	0.5	0.4
G	11		13	11	1.1	1.0
Elliot Lake						
VME	51	33	11	7	0.2	0.2
Q	na	50	na	13	na	0.3
S	59	45	21	8	0.3	0.2
PN	na	14	na	8	na	0.6
H2	17	14	9	7	0.5	0.5
T	na	15	na	7	na	0.5
Y	na	46	na	1	na	0.2
X	162	46	19	12	0.1	0.2
Control						
C1	12	18	9	10	0.7	0.5
C2	31		8	7	0.2	0.2
C4	31		9	9	0.3	0.3

Legend: na = no trees available from the tailings sites
Letters A to Z are site codes
C1, C2, and C4 are different control locations
TA = trembling aspen
WB = white birch
* mean concentration in trees/tailings or soil concentrations
** concentration in tailings for both trees

samples and the root region samples. For copper and nickel, the distributions of the concentrations are essentially uniform. Lead appears in higher concentrations ranges (300 to 400 μg/g) in a larger fraction of the tailings sites than in the soils.

TABLE 19 LEAD CONCENTRATIONS IN TREES GROWING ON TAILINGS, AND CONCENTRATION FACTORS

Site Codes	Tailings concentration (µg/g)		Mean Concentration All Parts (µg/g)		Concentration Factors*	
	TA	WB	TA	WB	TA	WB
Bancroft						
A1	71 **		6	8	0.1	0.1
C	104		11	60	0.1	0.6
D2	95		11	13	0.1	0.1
G	68		6	6	0.08	0.08
Elliot Lake						
VME	51	33	3	2	0.05	0.04
Q	na	434	na	18	na	0.04
S	374	179	11	8	0.03	0.04
PN	na	509	na	4	na	0.08
H	20	3	0.5	1	0.02	0.4
T	na	242	na	81	na	0.3
Y	na	891	na	20	na	0.02
X	48	72	nd	7	nd	0.09
Control						
C1	24	9	3	2	0.1	0.2
C2	32		nd	82	nd	2.5
C4	27		4	6	0.1	0.2

Legend:
na = no trees available from the tailings site
nd = not detected
Letters A to Z are site codes
C1, C2, and C4 are different control locations
TA = trembling aspen
WB = white birch
* mean concentration in trees/tailings or soil concentrations
** concentration in tailings for both trees

Metals or other potentially hazardous elements which reach the aerial parts of the plants are available to consumers (animals). The metals in *Typha latifolia* were

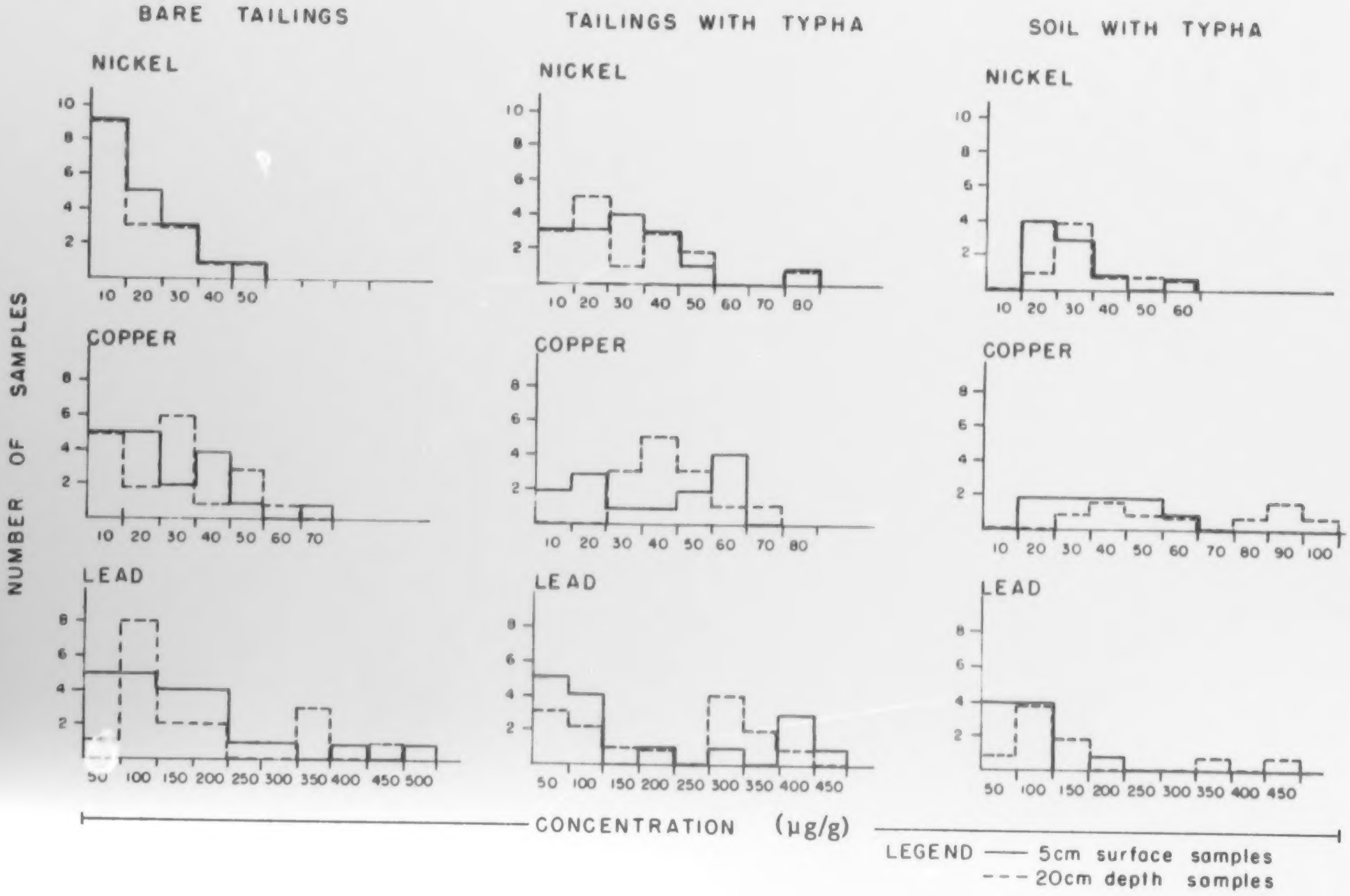


FIGURE 11 METAL DISTRIBUTIONS IN TAILINGS AND SOILS ASSOCIATED WITH *Typha* PLANTS

analyzed separately for the five organs of the plants, namely: roots, rhizomes, stems, leaves and seeds (Table 20). It is apparent that metals largely remain in the roots of *Typha latifolia*. However, a relatively small fraction of the total metal concentration does reach the aerial parts of a mature *Typha latifolia* plant.

Concentration factors were calculated for copper, nickel and lead based on the sum of all parts of *Typha latifolia*, and the average concentration of the surface and root region of tailings or soil samples. Some general observations are possible when concentration factors are plotted against the metal concentrations in tailings or soils (Figure 12). The concentration factors decrease for all these metals as the metal concentrations in the growth substrate increase from the lower ranges. As the substrate concentrations increase further, the relationship of the concentration factors to the substrate concentrations appears to differ for each metal. For copper, the concentration factor appears to remain at unity, but for nickel the values decrease below unity. For lead, the concentration factors appear to increase slightly with concentrations above 100 to 200 μg/g. These observations appear to hold for the plants both on tailings and on soils.

3.3.3 Radionuclides in *Populus tremuloides* and *Betula papyrifera*. The objective of radionuclide determinations in trees was mainly to assess the need for an investigation of the transfer of long-lived radioisotopes from the tailings to these plants. Such an assessment is important since trees were identified as major groups of plants naturally invading dry areas of inactive uranium mill tailings.

Difficulties encountered in the analyses of the results for metal concentrations in trees, with respect to the tailings areas, have been discussed earlier. The radionuclide concentrations determined in the trees are therefore compared for each collected specimen. The concentration of radium-226 in different plant organs (stems, leaves and roots) of both species are presented in Table 21. Both species of trees collected from the Bancroft tailings had significant radium-226 concentrations whereas approximately half of the trees from the Elliot Lake tailings had very low radium-226 concentrations. For example, trees on sites VME, S, X and H had concentrations essentially as low as the detection limit. The remainder of the trees collected here, all white birch specimens, exhibited concentrations of radium-226 which were somewhat lower than in the white birches from the Bancroft tailings sites. These observations are only valid relative to each other. The white birch collected on control site 2 had a concentration of radium-226 in the stem which was higher than in any of the trees

TABLE 20 PERCENTAGE OF METAL CONCENTRATIONS IN *Typha latifolia* ORGANS

Element	Growth location	Seeds	Stems	Leaves	Roots	Rhizomes
Cu	tailings	11 ± 7	8 ± 7	10 ± 8	61 ± 19	8 ± 4
	soil	23 ± 11	10 ± 3	13 ± 6	37 ± 22	16 ± 8
Ni	tailings	10 ± 8	7 ± 5	20 ± 14	53 ± 19	9 ± 4
	soil	18 ± 6	8 ± 9	19 ± 11	47 ± 21	8 ± 3
Co	tailings	7 ± 8	6 ± 5	12 ± 12	76 ± 15	6 ± 5
	soil	5 ± 3	4 ± 3	9 ± 5	73 ± 14	9 ± 9
Pb	tailings	2 ± 3	2 ± 2	4 ± 5	86 ± 10	5 ± 3
	soil	7 ± 5	5 ± 2	12 ± 8	69 ± 14	6 ± 3

collected from Bancroft or Elliot Lake tailings sites. This control tree sample suggests that radium-226 concentrations in trees are not at all related to the tailings. However, it is necessary to consider the possibility that the sample was mislabelled during the sample preparation. The control location should be resampled since the concentration of radium-226 clearly needs confirmation. In general, determinations of radium-226 in trees warrant further work. The radioisotope appears to be distributed throughout the tree organs.

The determinations of lead-210 in trees are presented in Table 22. Trembling aspens had generally lower concentrations of lead-210 than did white birches. The stems, leaves and roots had similarly low concentrations, often as low as 1 pCi/g dry weight. Of the 15 white birches analyzed, approximately half can be considered low in lead-210 concentrations, and the remainder had stems and roots with definite concentrations of the radionuclide. Trees with high and low concentrations, however, were found on tailings sites in both areas, indicating that there is likely no difference in uptake with respect to tailings area. Furthermore, the tree from control site 2 had the highest concentration of lead-210.

Radionuclides in trees of both species growing on tailings or control sites need to be considered in more detail. The data presented in this section only manifest the

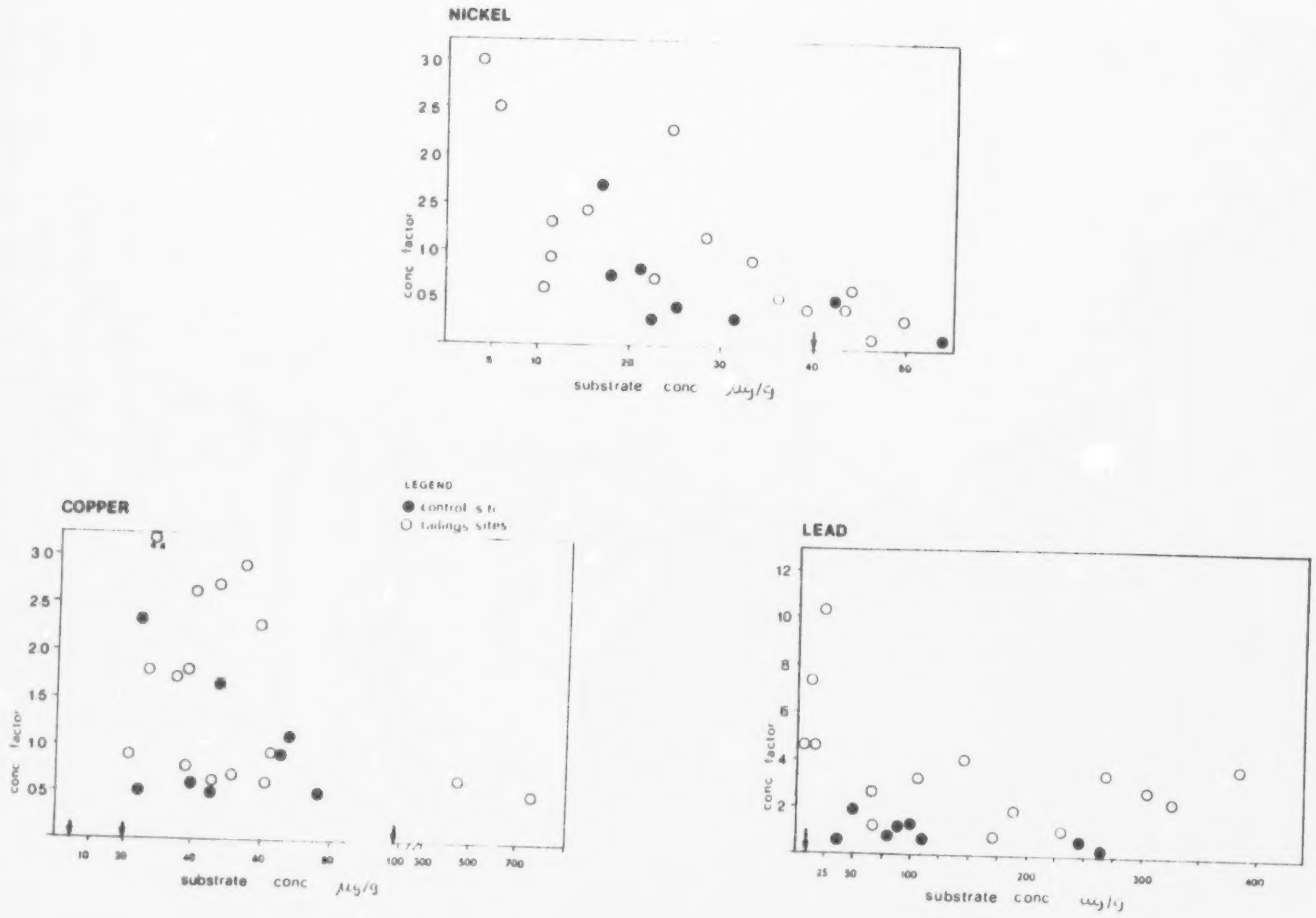


FIGURE 12 METAL CONCENTRATIONS IN TAILINGS RELATIVE TO CONCENTRATION FACTORS IN *Typha*

TABLE 21 RADIUM-226 CONCENTRATION IN DIFFERENT TREE ORGANS

Site Codes	Concentrations (pCi/g)					
	Stems		Leaves		Roots	
	TA	WB	TA	WB	TA	WB
Bancroft						
A1	45	57	33	135	38	47
C	8	26	22	22	11	15
D2	40	74	13	13	8	77
G	3	7	nd	nd	1	8
Elliot Lake						
VME	7	1	5	1	4	0.5
S	2	nd	1	5	5	2
X	0.5	nd	2	1	3	1
H2	2	nd	1	0.5	1	2
T	na	39	na	17	na	12
Y	na	5	na	6	na	10
PN	na	14	na	24	na	11
Q	na	10	na	15	na	10
Control						
C1	nd	nd	2	1	2	1.5
C2	nd	99	nd	44	nd	61
C4	3	2	3	5	2	1

Legend: na = no trees available from the tailings site
nd = not detected
The errors vary from ± (0.5 to 2.5) pCi/g for radium-226 determinations.
TA = trembling aspen
WB = white birch

presence of both radioisotopes in the tree organs, but give little indication that these concentrations are related to the tailings on which they grow. A more comprehensive treatment of these data awaits the analyses of the tailings or soils collected with the tree specimens.

TABLE 22 LEAD-210 CONCENTRATIONS IN DIFFERENT TREE ORGANS

Site Codes	Concentrations (pCi/g)					
	Stems		Leaves		Roots	
	TA	WB	TA	WB	TA	WB
Bancroft						
A1	3	3	2	7	1	2
C	2	19	2	16	2	10
D2	3	3	2	nd	1	3
G	1	1	1	0.5	1	0.5
Elliot Lake						
VME	3	0.5	1	0.5	3	nd
S	nd	5	2	3	7	6
X	1	0.5	nd	2	1	nd
H2	1	1	0.5	0.5	nd	0.5
T	na	19	na	6	na	24
Y	na	4	na	1	na	6
PN	na	26	na	4	na	16
Q	na	3	na	2	na	7
Control						
C1	1	1	1	2	0.5	nd
C2	nd	38	nd	6	nd	37
C4	nd	1	nd	0.5	1	2

Legend:
na = no trees available from the tailings sites
nd = not detected
The error for all lead-210 values range from ± (0.5 to 1.0) pCi/g
TA = trembling aspen
WB = white birch

3.3.4 Radionuclides in *Typha latifolia*. The uptake of radium-226 and lead-210 in this wetland species has been evaluated in more detail than in trees (Kalin and Sharma, 1981a). Some aspects of this work are presented here to facilitate a comparison of the concentrations determined in trees.

In *Typha latifolia*, the concentration ranges of radium-226 in five plant organs (roots, rhizomes, fruits, stems and leaves) were large. The absolute concentrations in the roots of the plants varied by a factor of 500. Concentrations as low as 0.5 pCi/g and as high as 250 pCi/g (dry weight) were determined.

In Figure 13, the cumulative percentage can be compared between the different plant organs and between the plants growing on tailings and soils. It is evident that the rhizomes, stems and leaves of *Typha* on the tailings, and the roots of *Typha* on soils, have a similar distribution of radium-226. The concentration ranges of radium-226 in leaves, rhizomes, stems and seeds of the plants growing on soil are generally lower than those of the seeds of the plants growing on tailings.

The distributions among *Typha* organs of lead-210 (Figure 14) are clearly more distinct than those of radium-226. Lead-210 is retained in the roots of plants growing on tailings. The rhizomes of those plants have the same distribution of lead-210 as the roots of plants growing on soil. The concentrations in the remaining plant organs are low and their distributions are very similar for both species growing on tailings or on soils.

Since most of the radionuclides are located in the roots, the uptake of both radium-226 and lead-210 was considered only with respect to the root concentrations. Absolute concentrations and concentration factors (concentration in root/concentration in tailings) are presented for radium-226 (Figure 15). The samples are arranged in decreasing order of radium concentration in the tailings and are identified by the site codes. Sites A to G are located in Bancroft, and Sites H to Z in Elliot Lake. The radium-226 concentrations and the concentration factors are not in any sequence, suggesting that radium-226 concentration are not related to the tailings areas. In 60% of the plants, the radium-226 concentrations are one or two orders of mangitude lower in the roots than in the tailings. The remaining 40% of the samples indicate higher concentration factors, with one extremely high value of 21. The collection of 15 plants and tailings samples originally from different tailings sites suggests that in most cases radium-226 is not taken up significantly by the plants.

Uptake of lead-210 by *Typha latifolia* is similar to that of natural lead. The concentrations of lead-210 are presented in the same format used for radium-226 (Figure 16). It is interesting to note that the sequence of the sample order changes. Thus, samples with high radium-226 concentrations are not identical to those with high lead-210

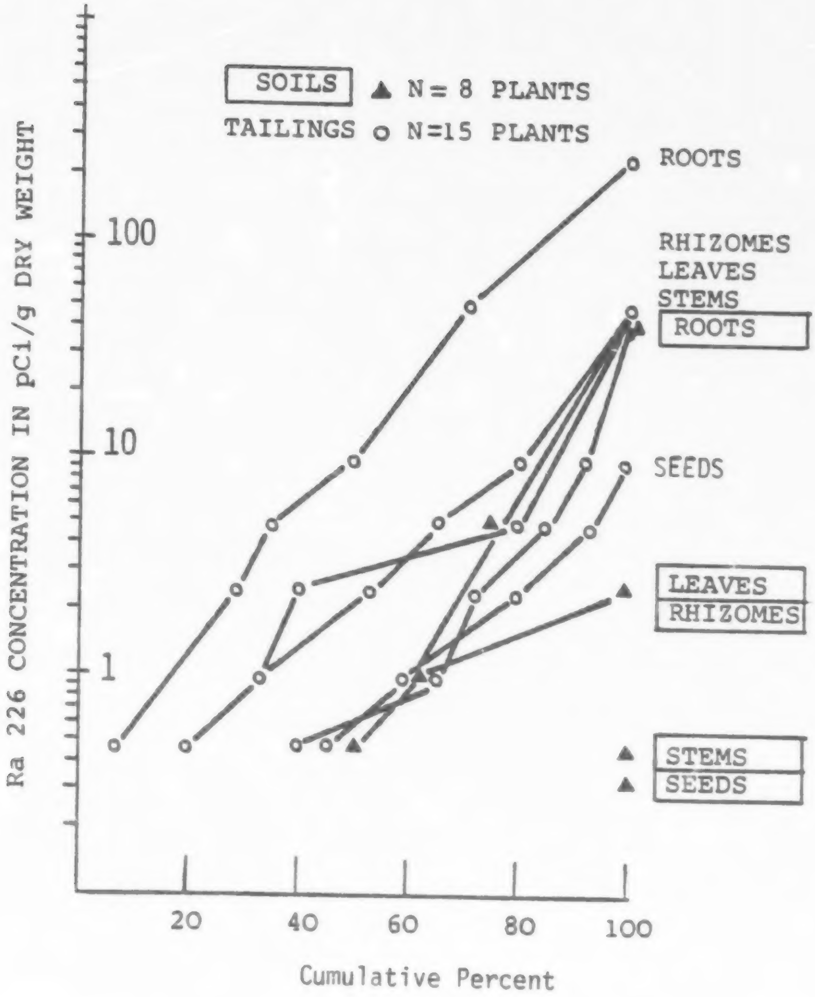


FIGURE 13 CUMULATIVE DISTRIBUTION POLYGON OF RADIUM-226 IN *Typha latifolia* PARTS

concentrations. The concentration factors in plants collected on sites A and G are high for both radionuclides, which is not the case for other high concentration factors.

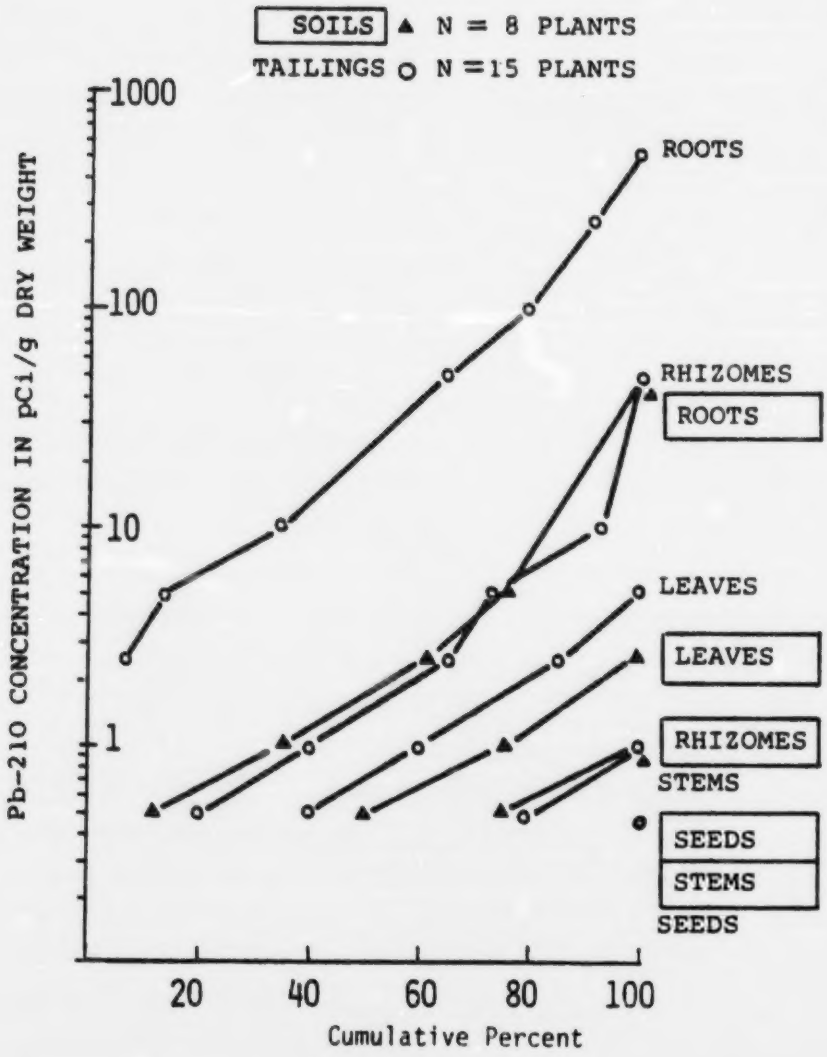


FIGURE 14 CUMULATIVE DISTRIBUTION POLYGON OF LEAD-210 IN *Typha latifolia* PARTS

The concentration of radium-226 and lead-210 in soil and the concentration factors for *Typha latifolia* are arranged in decreasing order of radionuclide concentration (Figure 17). Radium-226 and lead-210 concentrations again do not correspond with

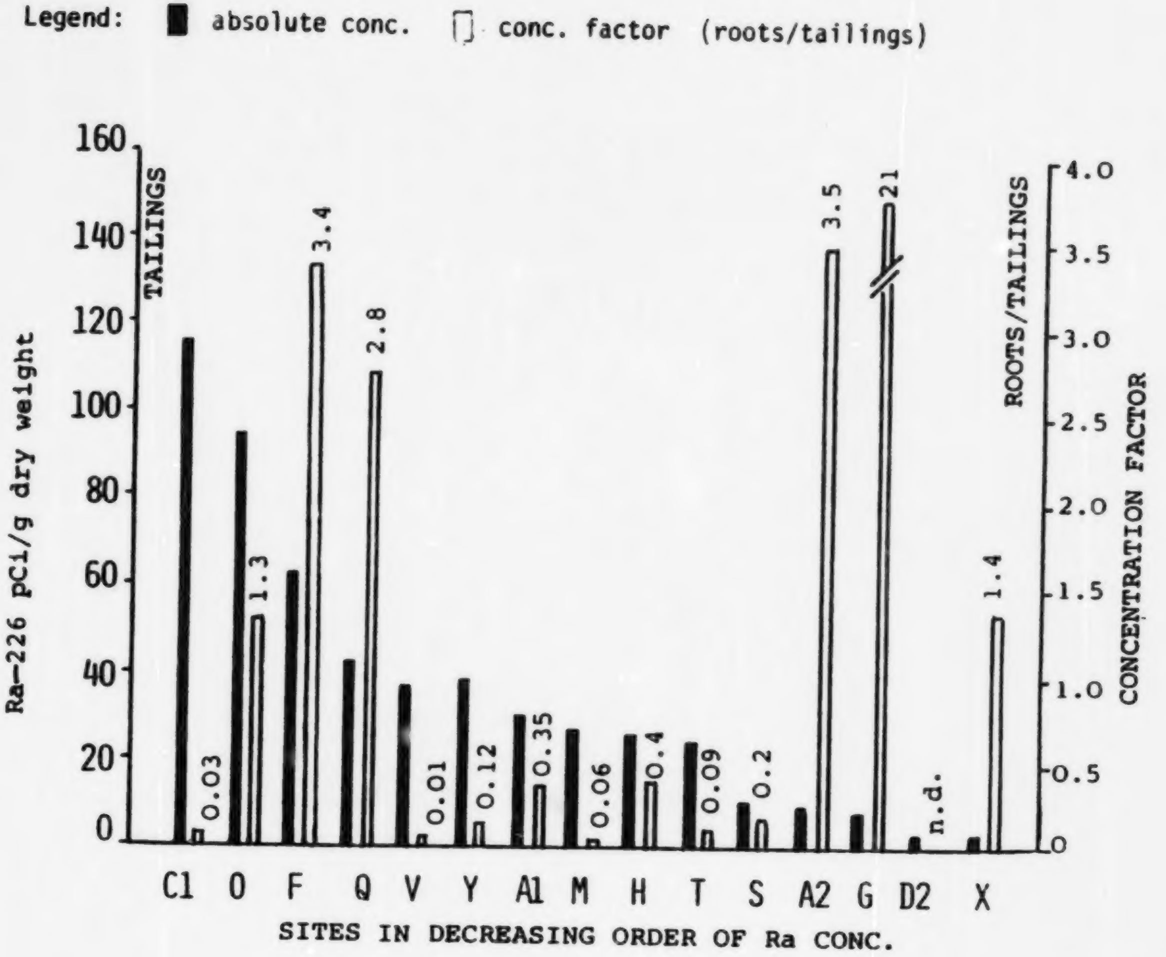


FIGURE 15 RADIUM-226 IN TAILINGS, AND CONCENTRATION FACTORS

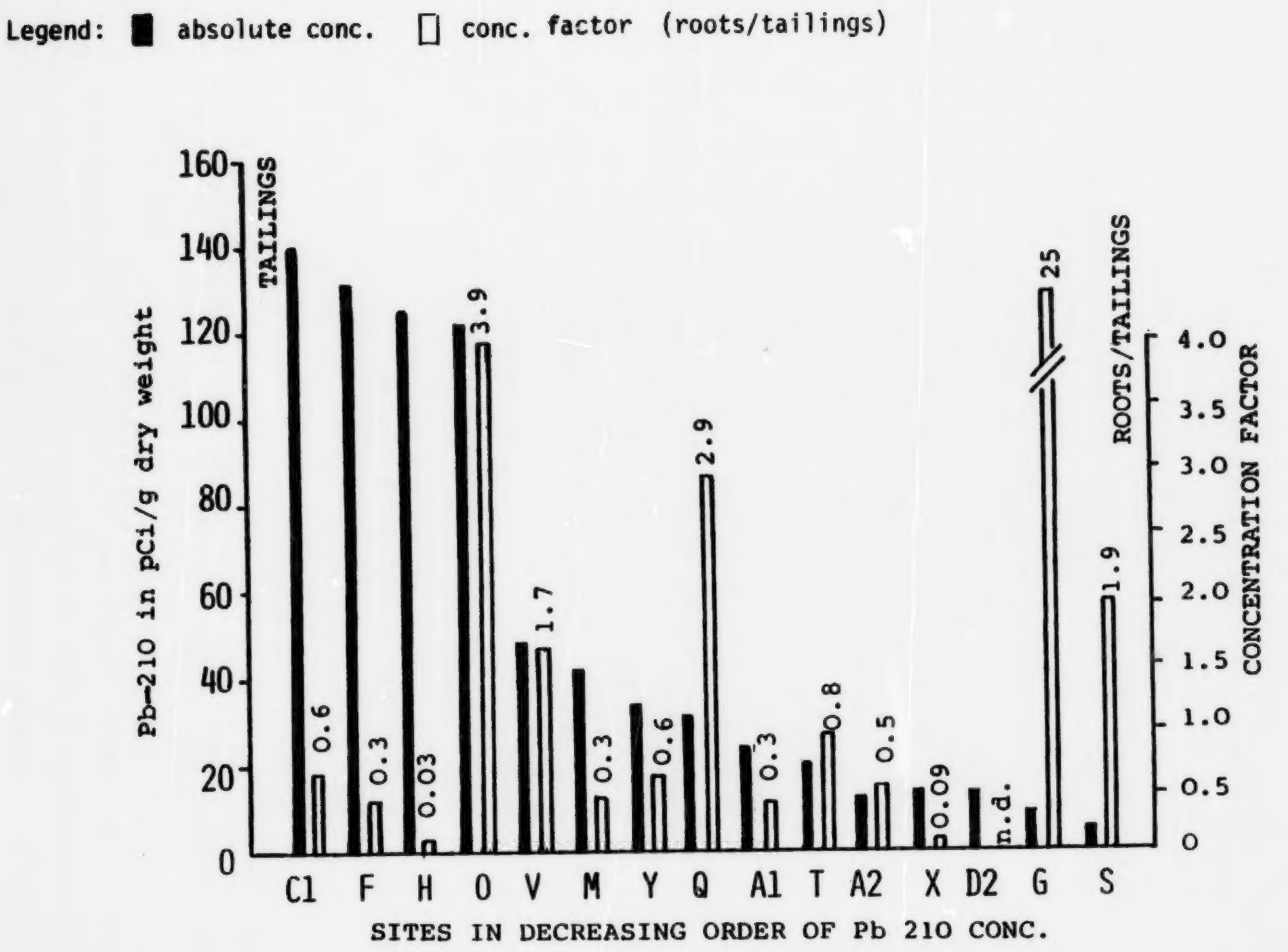


FIGURE 16 LEAD-210 IN TAILINGS, AND CONCENTRATION FACTORS

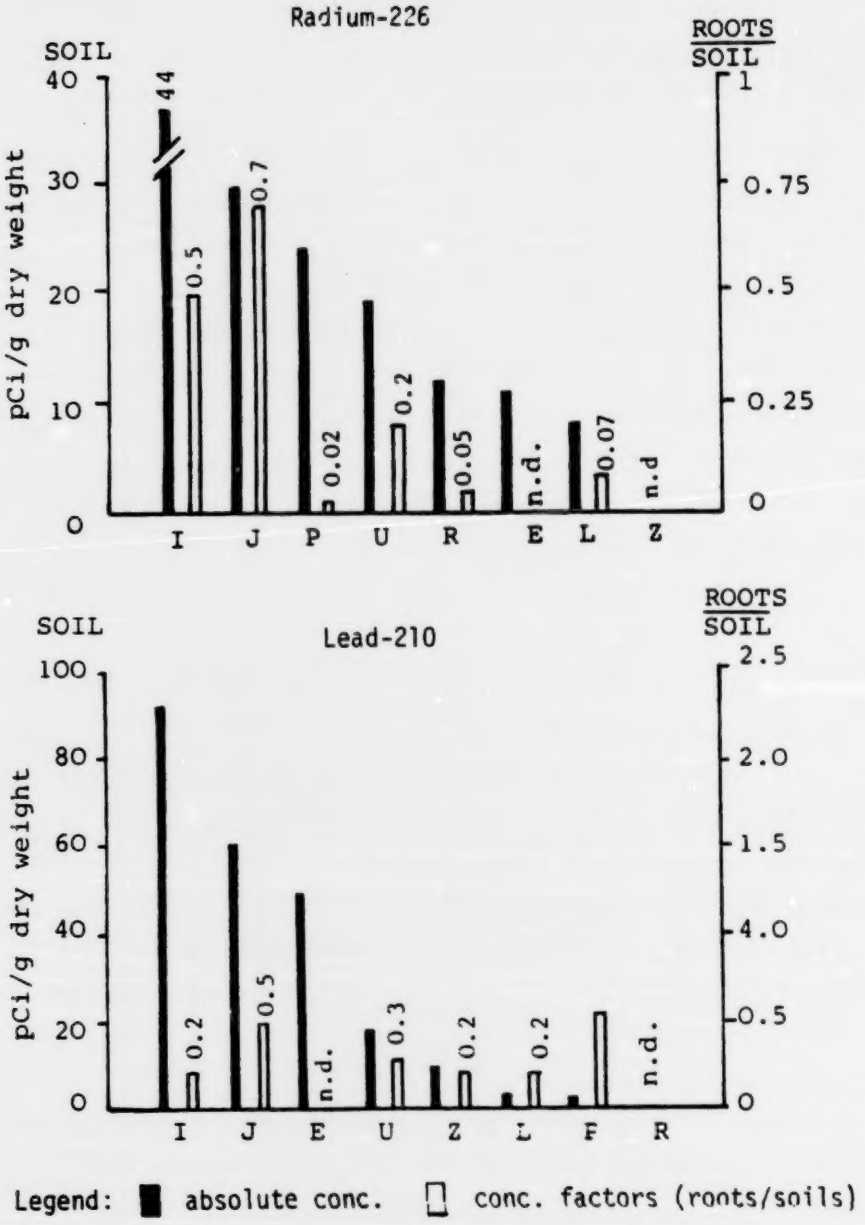


FIGURE 17 RADIUM-226 AND LEAD-210 IN SOIL, AND CONCENTRATION FACTORS

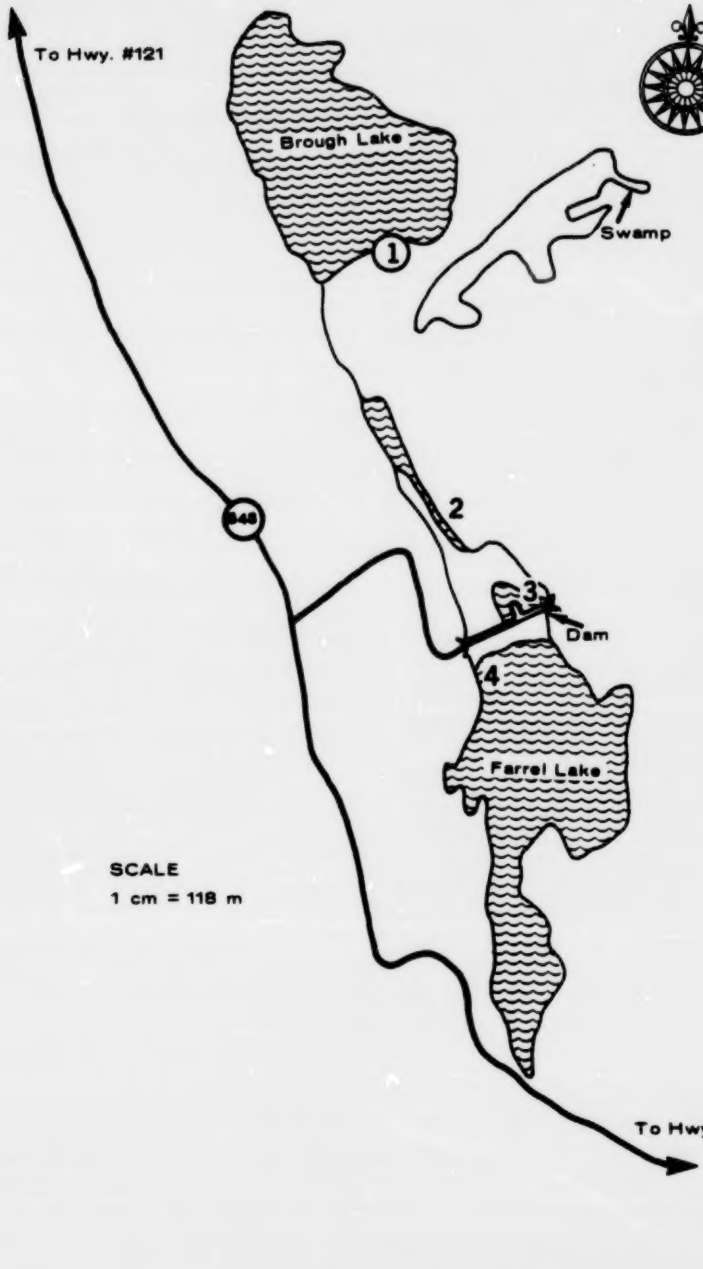
respect to their total concentrations in soils. The concentration factors for radium-226 vary but are generally well below unity whereas for lead-210, they are consistently around 0.2-0.5. Some samples had concentrations below the limits of detection.

3.4 Water on Abandoned Tailings

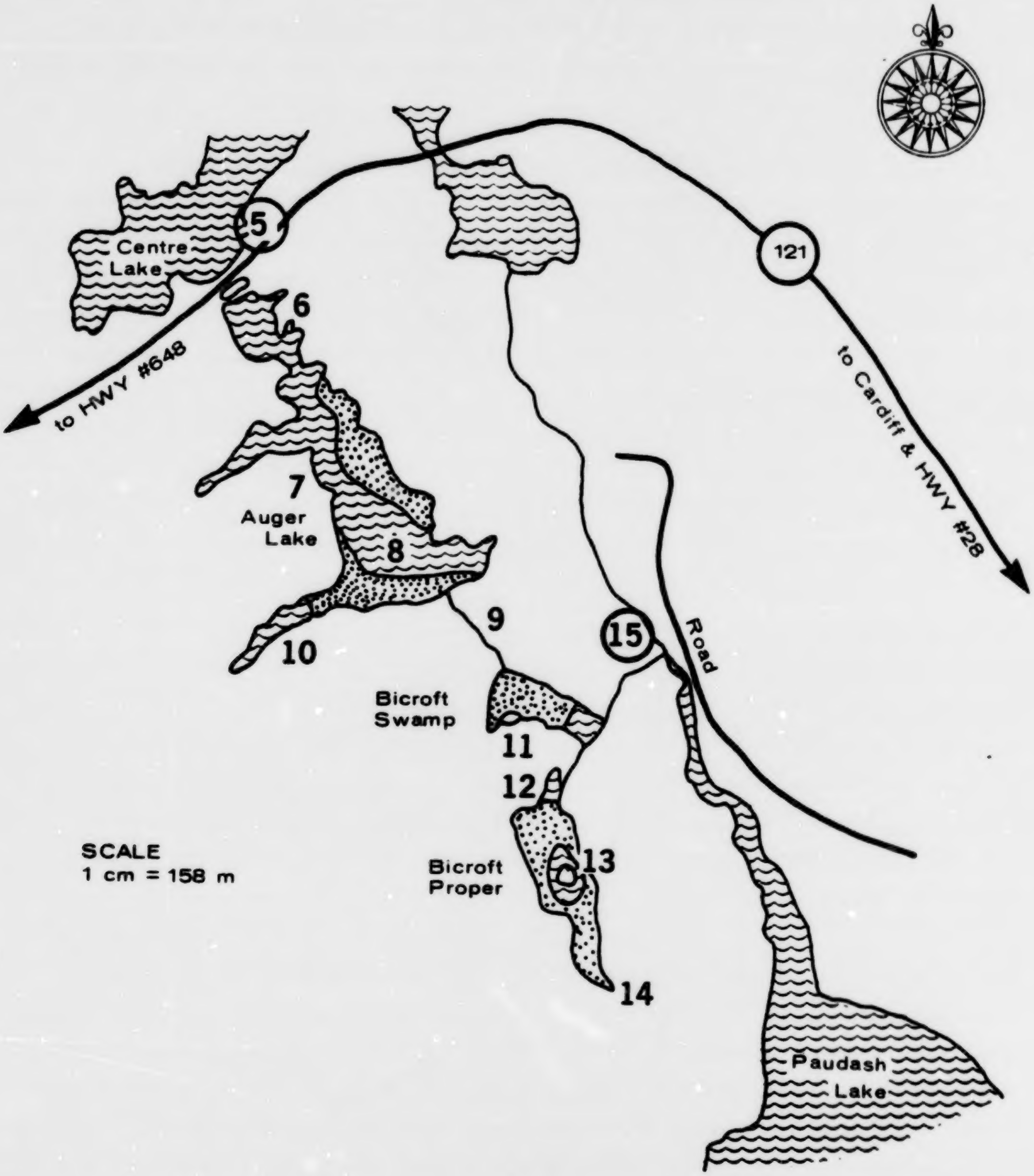
Water bodies of different sizes are associated with the tailings. They were discussed in Section 3.1.4 with respect to occurrence, location, origin and significance to biota. The tailings have been characterized to a degree as a growth substrate for vegetation. Some phenomena of water in contact with the tailings were outlined in Section 3.2.2. Water on uranium mill tailings is considered an important aspect of the abandoned tailings ponds. Selected aspects of water have been investigated during this survey, mainly with the objective of describing characteristics of the water which are of significance to biota and to ecosystems which may receive water from the tailings. The sampling program aimed to determine differences in water in the absence of treatment of tailings effluents and treated water. Seasonal changes in the water bodies were assessed, based on three sampling periods. Water was collected from the same location before spring run-off, shortly after melting of the ice, and at the end of the summer of 1980.

3.4.1 Sampling Locations and Surface Water Flow Direction. Most sampling locations were marked with floats. The locations were chosen to determine the characteristics of surface water flowing into the tailings pond, water remaining on the tailings pond, and finally the water leaving the pond in the form of a creek or a seepage. The sampling locations were numbered, starting in the Bancroft area with Brough Lake (1) (Map 18) which drains mainly towards the Dyno tailings. A creek (2) runs into Dyno (3), where water is retained by a dam. The remaining part of Farrel Lake was sampled some distance away from the dam (4). Dyno represents a reasonably defined system of surface water flow.

The water in Auger Lake appears to be mainly from ground seepage. This lake is not connected to any other lake by surface water flow (Map 19). Auger Lake drains in a northern direction towards Centre Lake (5) through a dam and retaining pond. Auger Lake was sampled in four locations, sites (6) to (10). A seepage leaves at the foot of the south dam (9). This creek also receives water from a decant structure at the south end of Auger Lake. A small shallow open water body located on Bicroft Swamp (11) was sampled. This is a collection of water draining from Auger Lake and Bicroft Proper (12) tailings ponds. On Bicroft Proper, water was collected (13) in a small open water body. A seepage to the


To Hwy. #121
Brough Lake
①
Swamp
2
648
3
Dam
4
Farrel Lake
SCALE
1 cm = 118 m
To Hwy. #28

MAP 18 WATER SAMPLING LOCATIONS (Dyno Mines Limited). Tailings Site No. 15. Source: Aerial photograph, No. 7744-39, 16,144.


Centre Lake
5
6
to HWY #648
7
Auger Lake
8
9
10
121
to Cardiff & HWY #28
15
Road
Bicroft Swamp
11
12
13
Bicroft Proper
14
SCALE
1 cm = 158 m
Paudash Lake

MAP 19 WATER SAMPLING LOCATIONS (Bicroft Mines Ltd.). Tailings Sites No. 12 - 14. Source: Aerial photograph, No. 77-4441, 33-108.

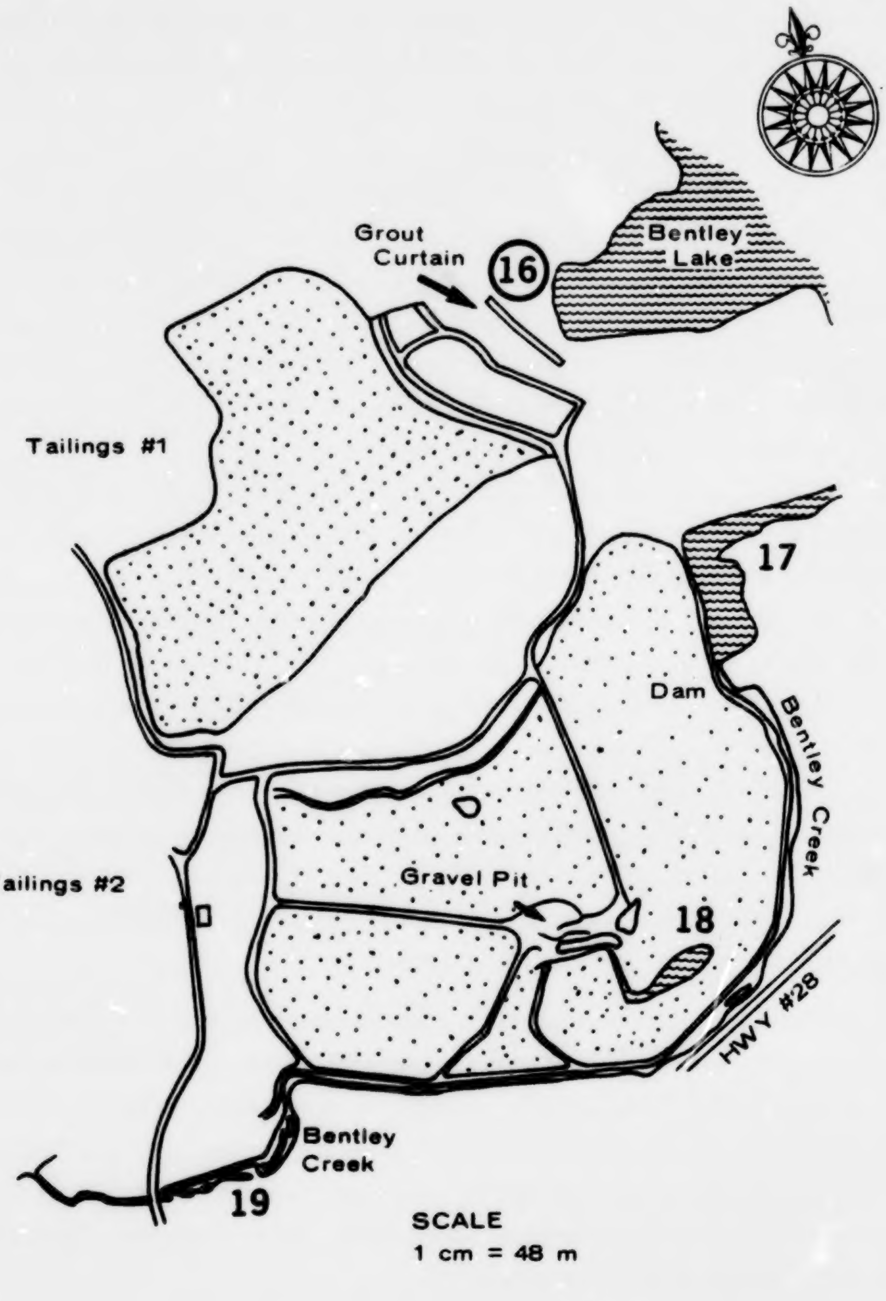
south at the foot of a steep dam was also sampled (14). As a control point, Deer Creek (15), which originates in Centre Lake, was sampled. Sampling sites which are considered control sites, or sites likely not affected by tailings material, are indicated on the maps with encircled numbers (i.e. Sites 1, 5 and 15).

The water sampling locations of the Madawaska tailings ponds are indicated in Map 20. Pond 1 is an active tailings pond. A grout curtain and other structures prevent flow from the active tailings pond into Bentley Lake, sampling location (16). This sampling location was compared to locations (17) and (19), where a dam separates the inactive tailings pond 2 from the creek. Bentley Creek originates in Bentley Lake and runs along the dam of the tailings pond 2. Location (18) in a small puddle of water which remains on the tailings pond throughout the season.

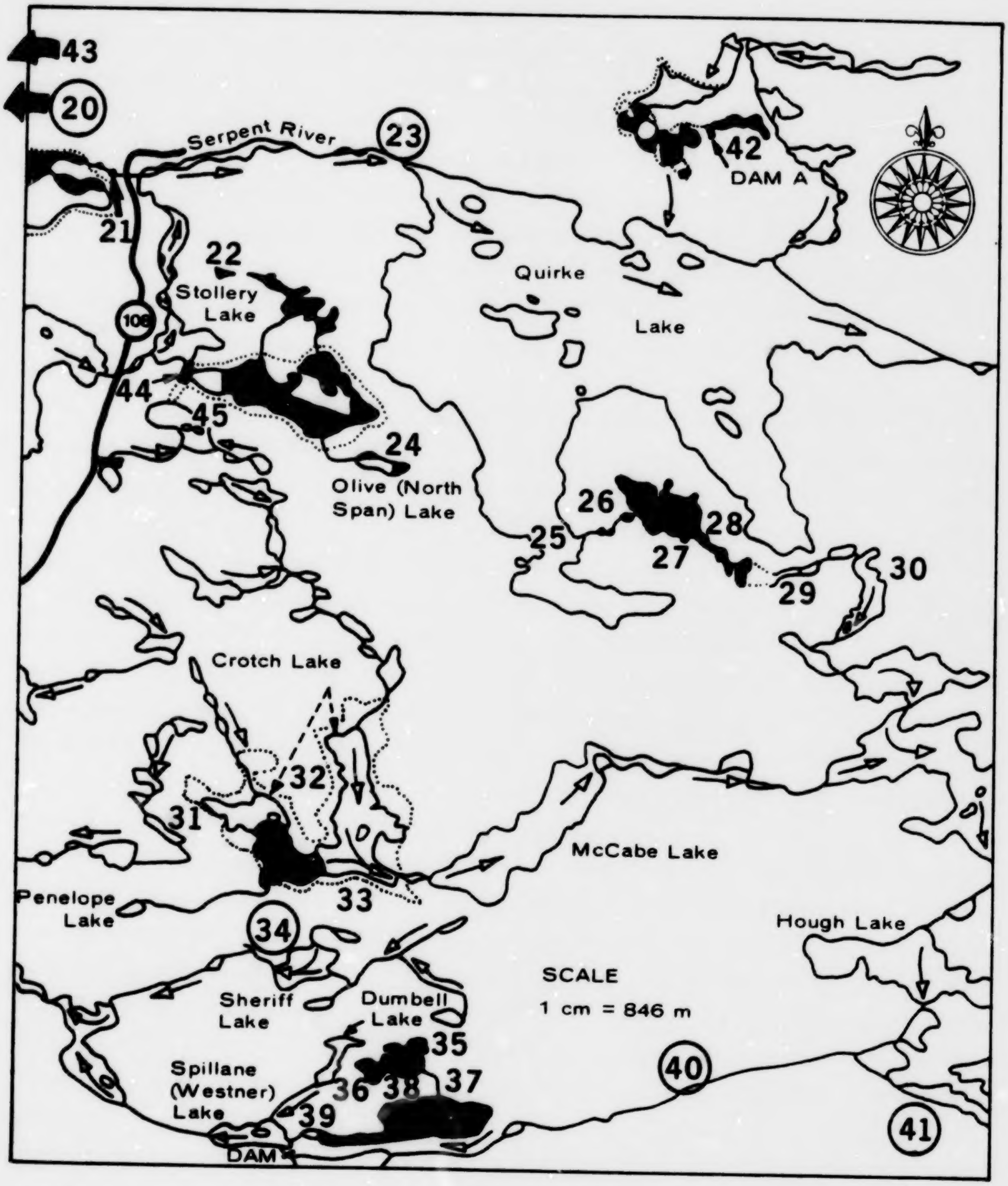
In the Elliot Lake area, the surface water flow from the inactive tailings could only be considered in the immediate vicinity of the tailings ponds. To sample each tailings pond as detailed as on the Bancroft sites was beyond the scope of this survey. The concept used in the Bancroft area was generally applied to the Elliot Lake area. However, there the situation was often more complex. For example, the incoming surface water on one tailings site can originate from other tailings ponds, to be collected in one seepage pond for treatment. All the water leaving the tailings pond is treated. Sampling locations were chosen with the main objective to avoid interference due to treatment of the tailings water. The sampling locations for each tailings pond are given in Map 21. The control locations 20, 34, 40 and 41 represent samples of lakes and creeks, to provide general background values for the area. Location 23 served as a reference sample, as this point is frequently sampled for water quality monitoring.

3.4.2 Characteristics Which Group the Surface Water Samples. Conductivity and pH of water samples appeared to be characteristics of water which could be connected functionally to the origin of the samples. Groups of samples were formed, based on the nature of the contact with the tailings described as "water on tailings" and "seepages and seepage ponds". A further group was formed out of all "control" samples. A last group was formed of those samples collected downstream from treatment facilities, thus reflecting water characteristics after treatment.

The pHs of these groups are presented, indicating seasonal changes by the direction of the arrows in Figure 18. Three sampling intervals in one season indicate only general trends. Large changes in pH values are observed in the water after treatments. All other groups exhibit a consistency in the pH value over the season. The pH measured


Grout Curtain
16
Bentley Lake
Tailings #1
17
Dam
Bentley Creek
Tailings #2
Gravel Pit
18
HWY #28
Bentley Creek
19
SCALE
1 cm = 48 m

MAP 20 WATER SAMPLING LOCATIONS (Madawaska Mines Limited). Tailings Site No. 11. Source: Stokes and Kalin (1978) modified.


43
20
Serpent River
23
42
DAM A
21
22
Stollery Lake
108
Quirke
Lake
44
45
24
Olive (North Span) Lake
26
28
25
27
29
30
Crotch Lake
32
31
McCabe Lake
Penelope Lake
33
34
Hough Lake
SCALE
1 cm = 846 m
Sheriff Lake
Dumbell Lake
35
Spillane (Westner) Lake
36
38
37
39
40
41
DAM

MAP 21 WATER SAMPLING LOCATIONS (Rio Algom Ltd. & Denison Mines Ltd.). Tailings Sites No. 1 - 10 (from Environmental Assessment Board (1979), modified.

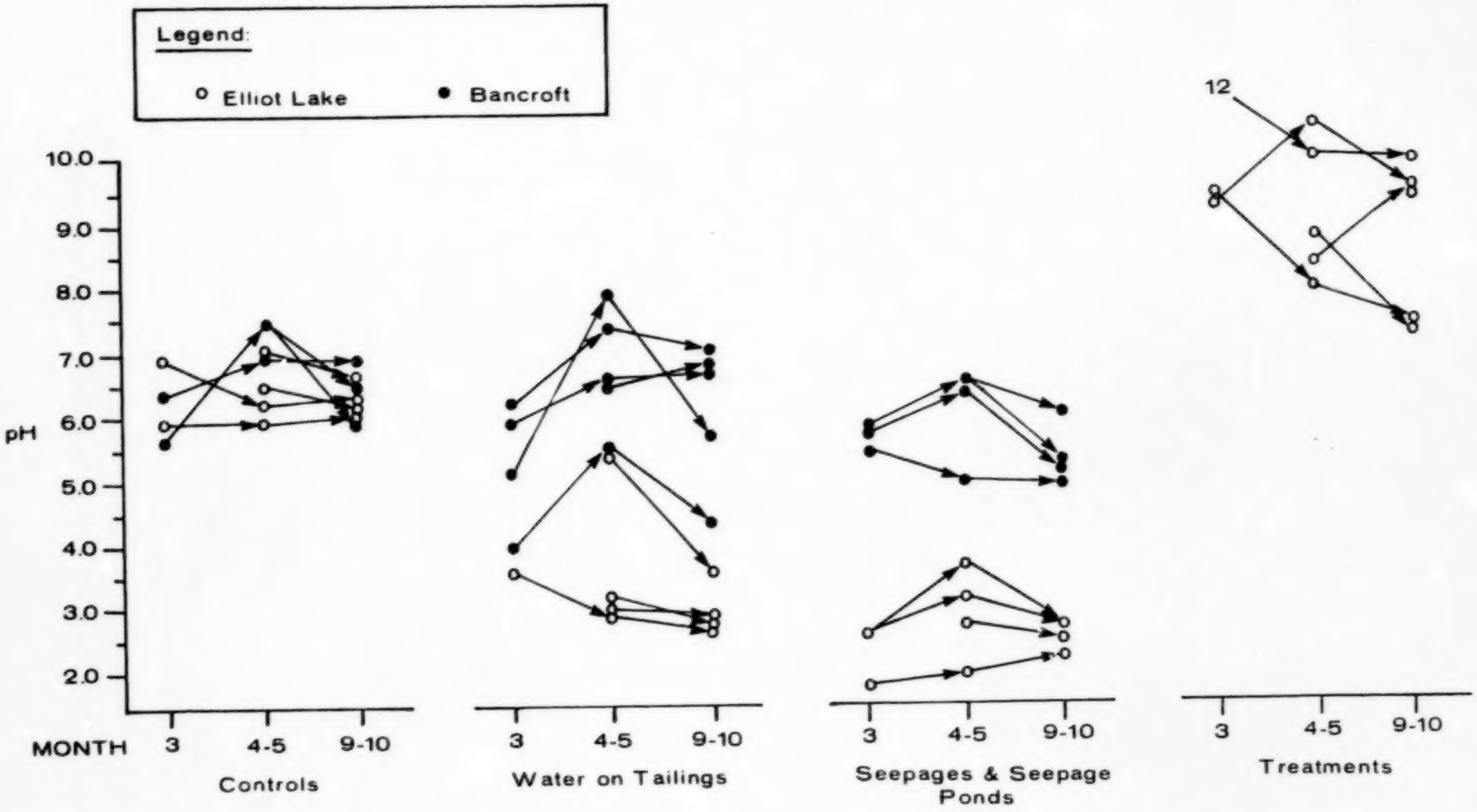


FIGURE 18 pH DETERMINATION OF GROUPS OF WATER under the ice increases slightly after run-off and returns in autumn to the same value as in early spring. One location deviates from this pattern. In the control group (Brough Lake), which drains into Dyno, pH increases from 5.5 to 7.5 after run-off, returning to 5.5 in autumn. This is a considerable change compared to the other control locations. A similar change can be noted in the group "water on tailings". On Dyno the water appears to undergo a corresponding change in pH similar to that of Brough Lake.

The tailings water in the Bancroft area is generally less acidic than in the Elliot Lake area. The seepage water leaving the tailings pond reflects the pH values of the water on the tailings pond. The slight seasonal variation observed might be directly related to precipitation. In essence, the pH values of these water groups can be considered to be quite consistent.

The conductivities of the water for the different groups are represented in the same way as the pH values (Figure 19). Seasonal changes occur in the seepages and seepage ponds. The reductions in conductivity are likely an effect of spring run-off as the conductivities increase again toward the end of the season to values determined under the ice or in winter with reduced water flow. The conductivities change essentially by one order of magnitude between each group of water samples. The lowest conductivities are found in the control waters and most treated waters have conductivities as high as the seepages. For one seepage, a conductivity value larger than 10 000 µmhos/cm was consistently determined. Comparing the tailings areas with respect to the conductivity of the water on the tailings, the group seepages and seepage ponds are generally in the same ranges for Bancroft and Elliot Lake. The pH values, on the other hand, indicated a distinct difference between the areas (Figure 18).

Chlorophyll *a* determinations can be used as an indicator of algal biomass. Given the pH and conductivity values of the tailings water, it can be expected that the biomass production is low. The water on tailings yielded chlorophyll *a* concentrations in ranges quite comparable to the control sample locations (Figure 20). This is also the case for most of the seepages and seepage ponds. The lowest values of chlorophyll *a* were determined in treated water. The direction of the change noted between the samples collected in early summer, and in autumn are extremely varied, and may warrant further analyses.

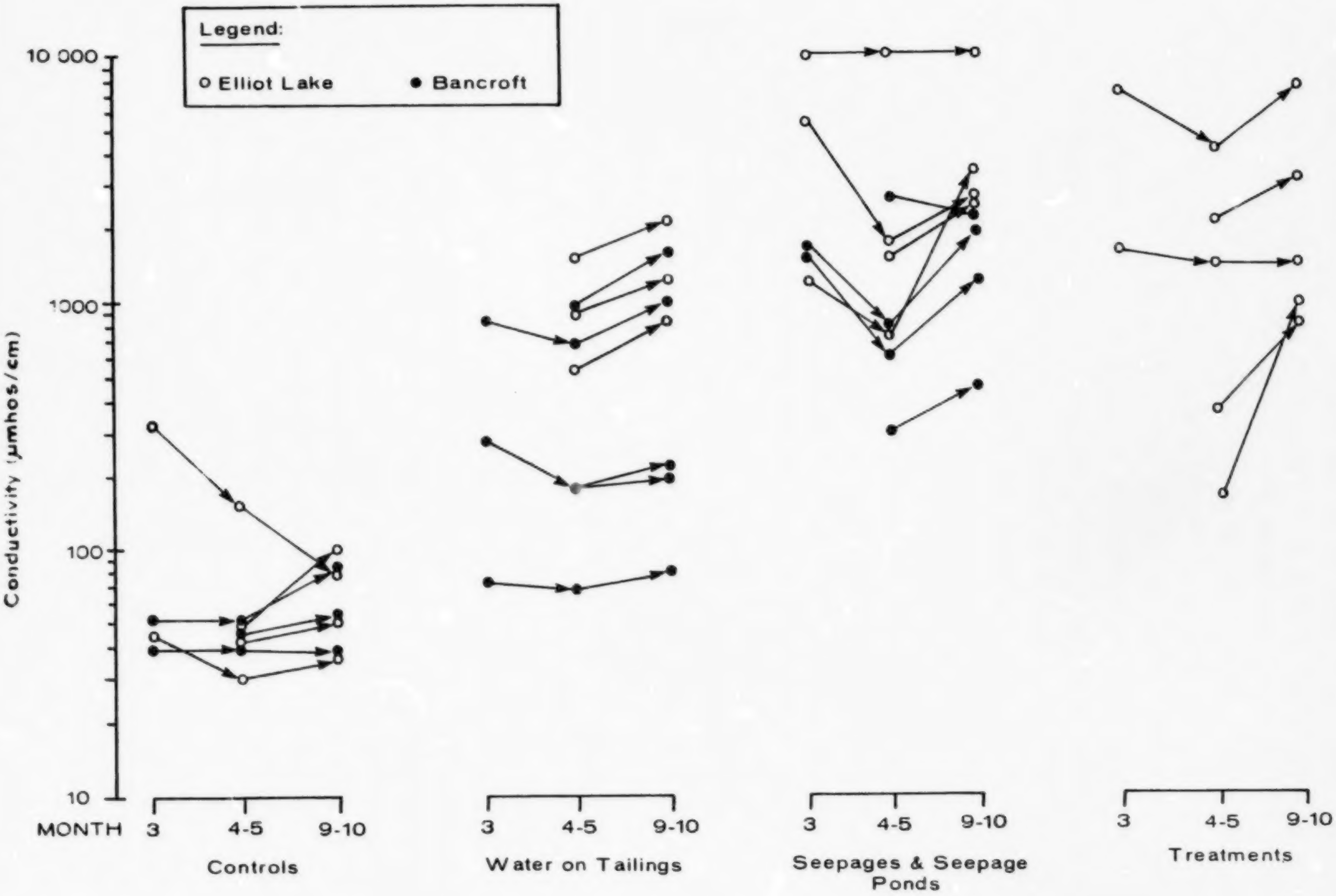


FIGURE 19 CONDUCTIVITY OF GROUPS OF WATER

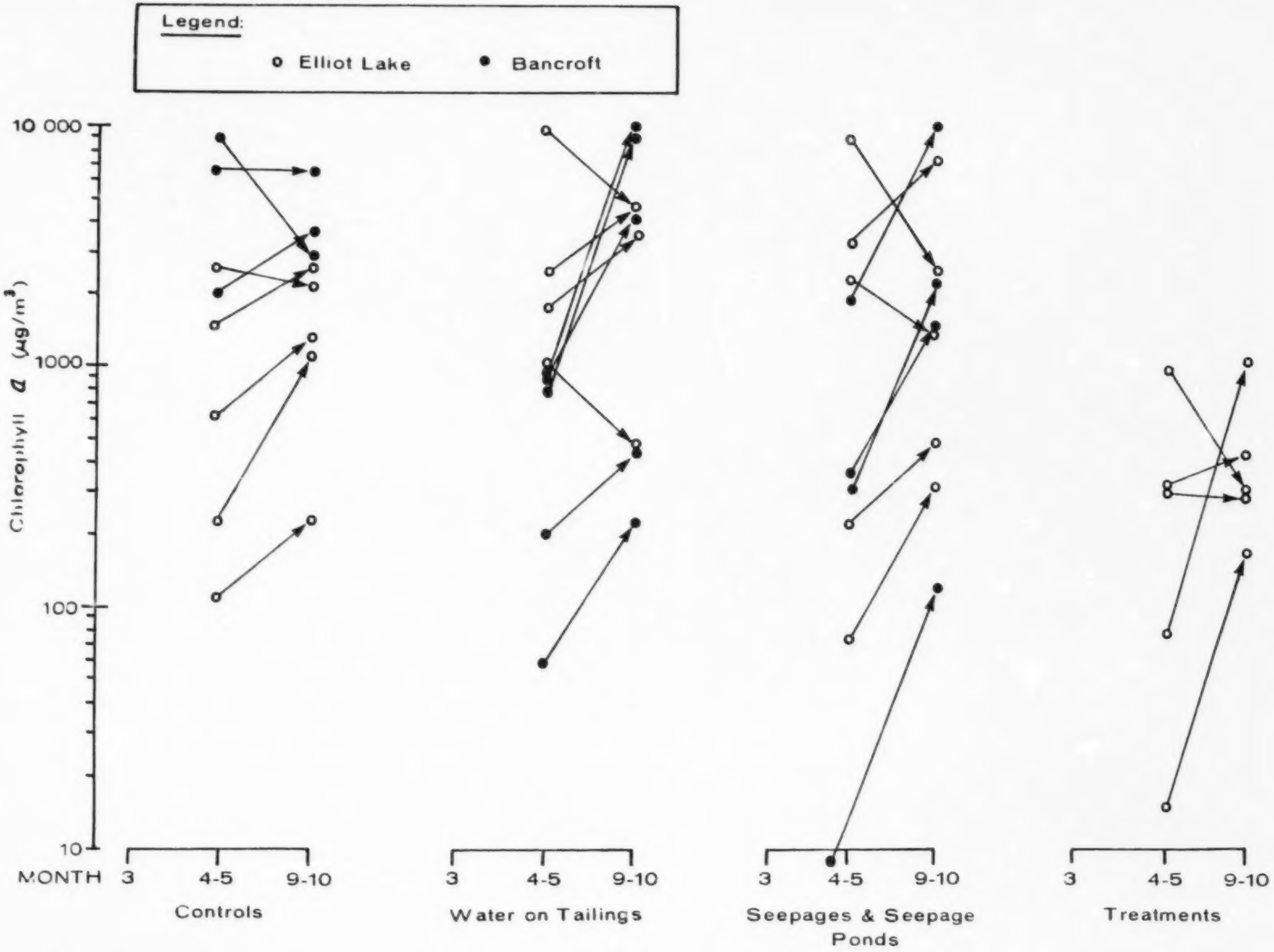


FIGURE 20 CHLOROPHYLL *a* DETERMINATIONS OF GROUPS OF WATER

3.4.3 Relationships Between Characteristics of Water Associated with Tailings. The values of pH and conductivity of the water from the same locations were similar at the beginning and at the end of the season (Figures 18 and 19). Dissolved matter was determined in a subset of samples and the values are compared for the spring and fall collections (Figure 21). The groups of water on tailings and control locations are compared for Bancroft and Elliot Lake, separately to the treatments and seepages for both areas. The values for the former groups of water were generally well below 1 g/L, and were identical at the beginning and at the end of the season. The groups treated water and seepages, however, exhibit a distinct increase in dissolved matter for the fall. The seasonal changes in precipitation affect treated water and seepages; this does not appear to be the case for water on tailings. Factors controlling the characteristics of the seepage water from the tailings pond warrant further investigation.

The dissolved matter was also correlated to the pH of the water (Figure 22). As dissolution is influenced by the hydrogen ion concentration, the noted quasi-linear relationship of pH and dissolved matter is expected. The hand-fitted curve displays a considerable amount of scatter which reflects the different water-tailings contacts (ponds, creeks, etc.). The dissolution of matter from the tailings by the water and the pH of the water are likely not controlled by the same factors, thus resulting in the observed scatter.

Conductivity of the water is an expression of the presence of dissolved electrolyte. Thus, the linear relationship of dissolved matter with conductivity indicates that the tailings water contains mainly electrolytic salts (Figure 23). Given these relationships of pH, conductivity and dissolved matter in water associated with tailings, it is possible to determine from one of these three measurements the related characteristics of the surface water within a reasonable range. Clearly statistical analyses of the complete data set are necessary; confirmation of the relationships may be desirable.

The behaviour of dissolved matter in surface water of differing origins exhibits a consistent pattern. The frequency distributions of total and dissolved matter collected in the spring and the fall are very similar (Figure 24). In both seasons, most of the samples collected had concentrations of both matters below 1 g/L. Given the similarity in the distributions of dissolved and total matter, total matter was compared in identical pairs of samples (i.e. water collected at the same time in the same location) (Table 23).

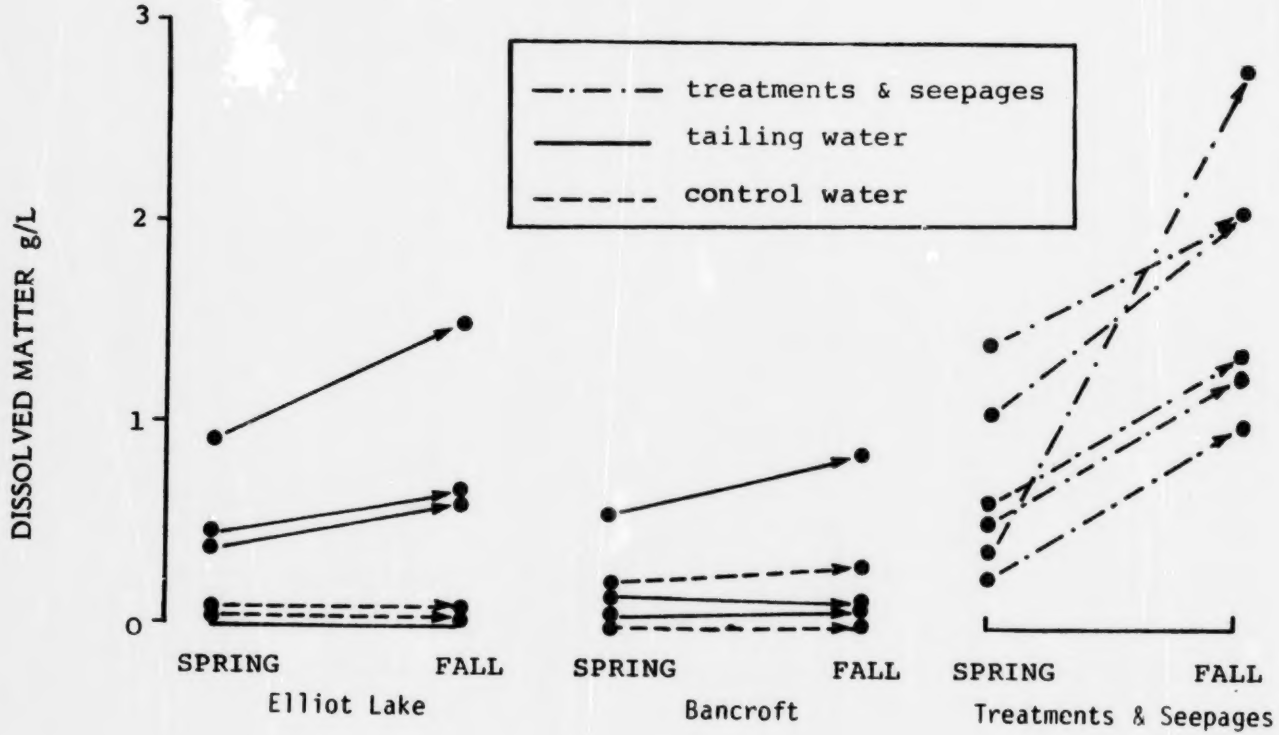


FIGURE 21 CHANGES IN DISSOLVED MATTER FROM SPRING TO FALL (1980)

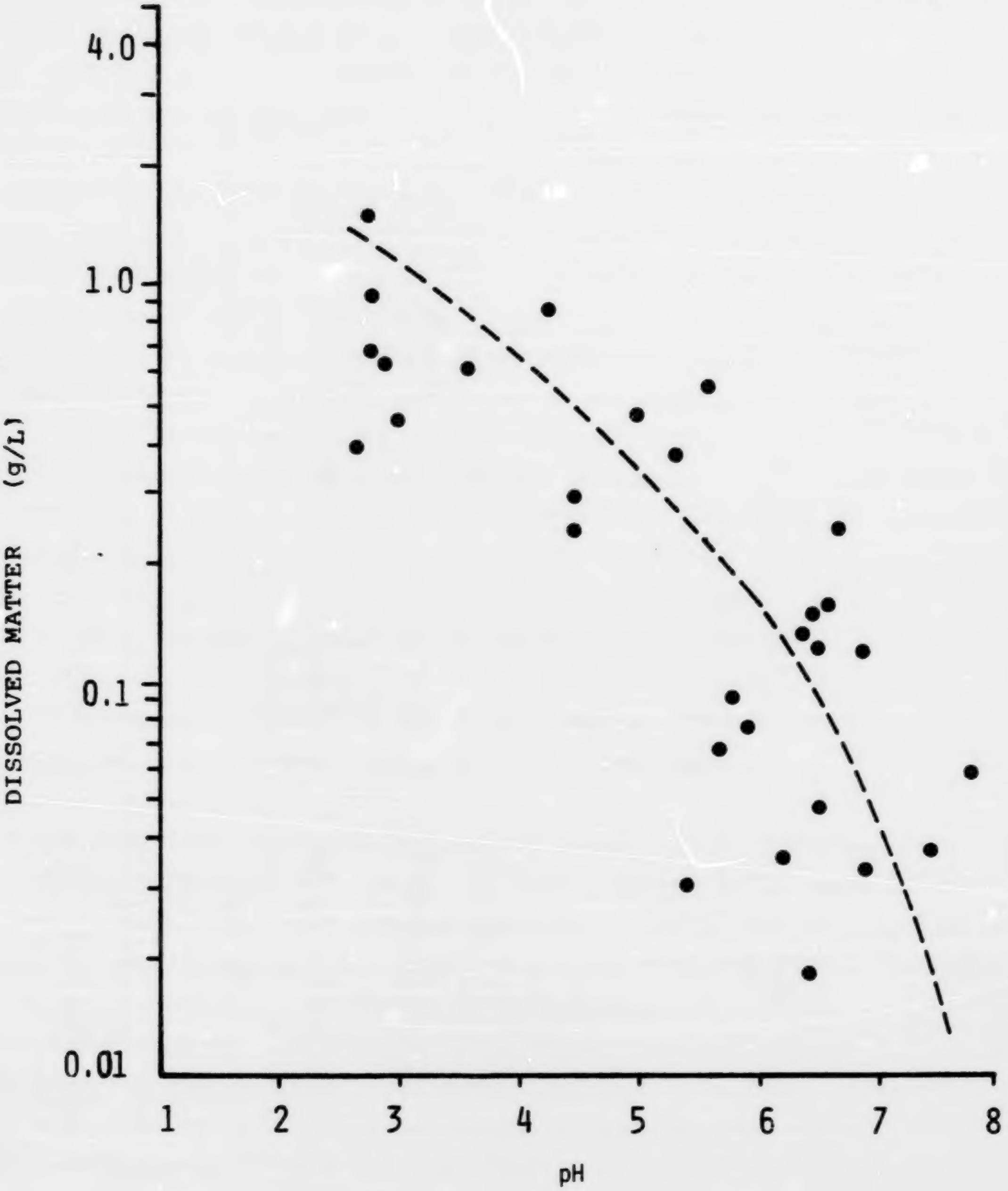


FIGURE 22 DISSOLVED MATTER IN RELATIONSHIP TO pH OF WATER

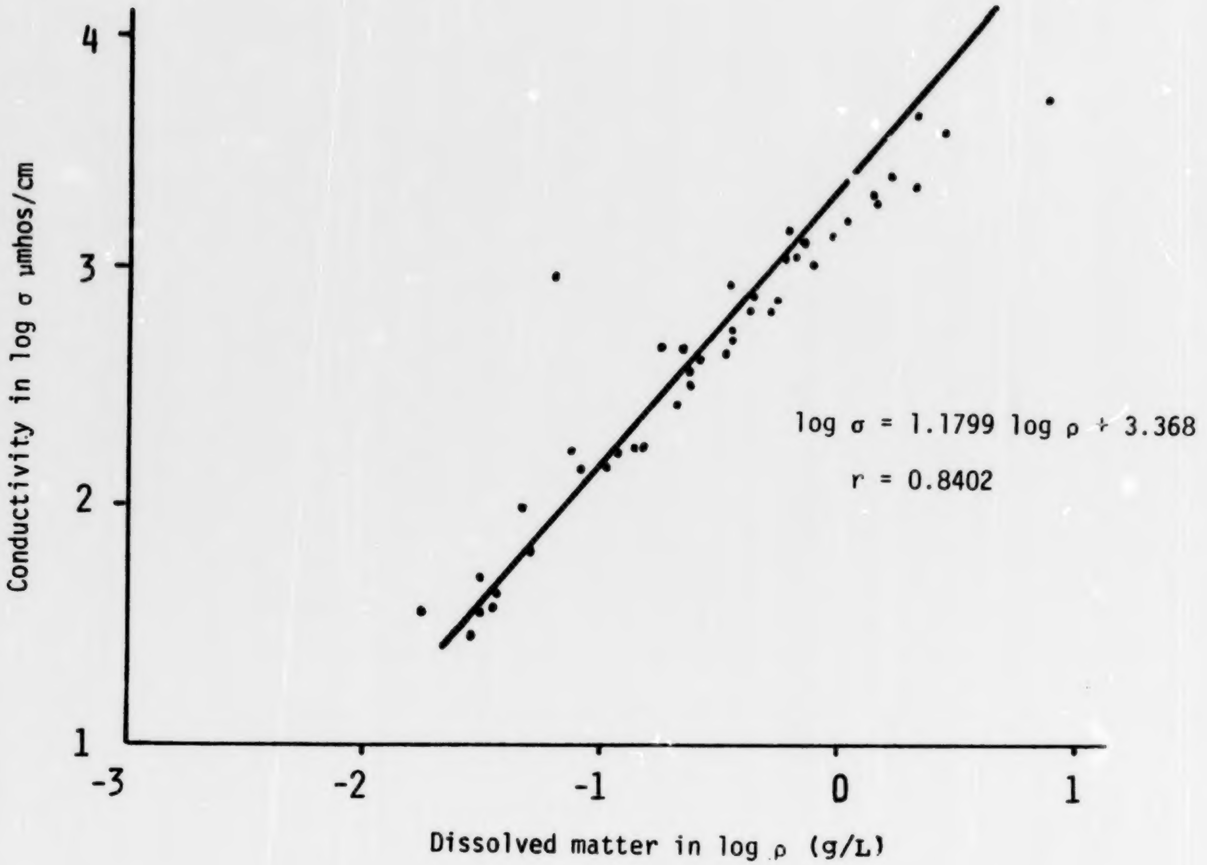


FIGURE 23 CORRELATION OF DISSOLVED MATTER AND CONDUCTIVITY OF ALL COLLECTED WATER

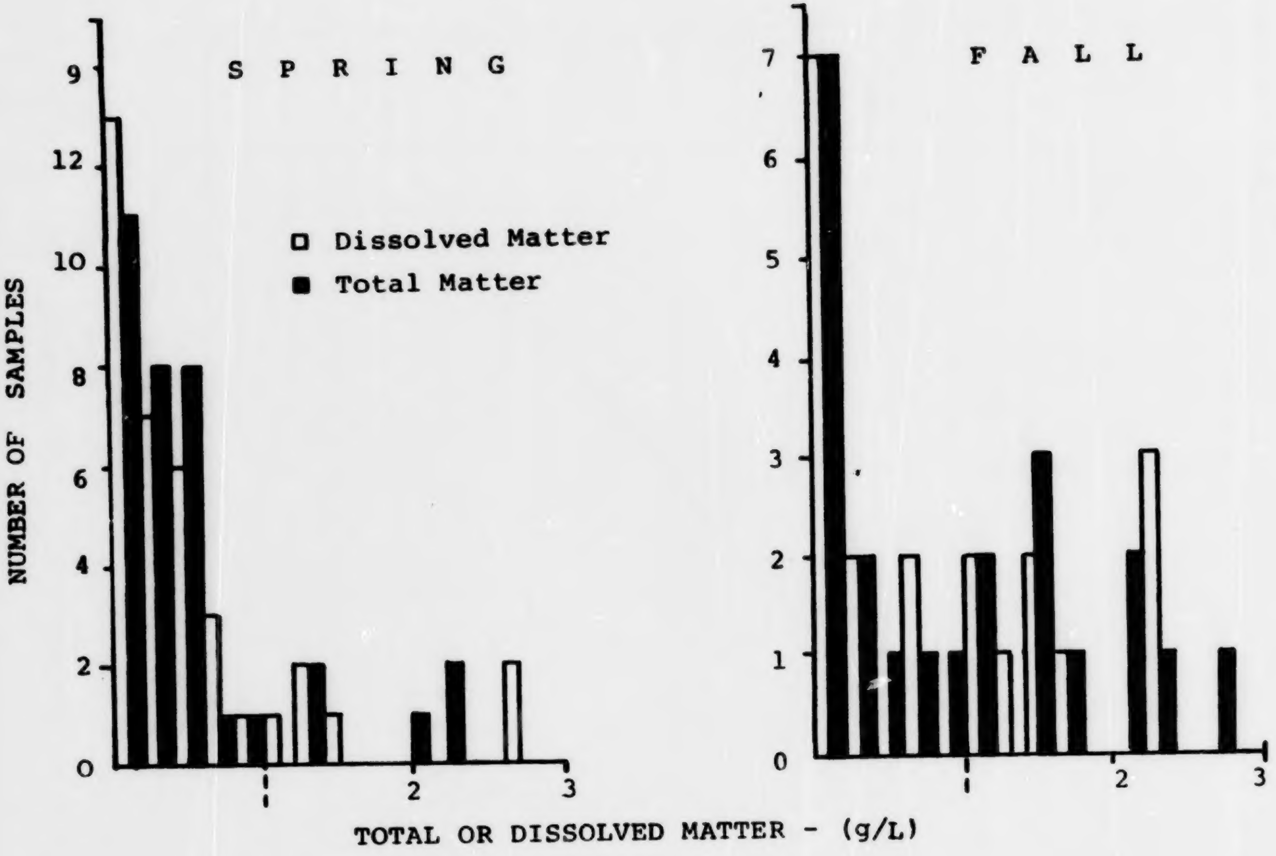


FIGURE 24 DISTRIBUTION OF TOTAL AND DISSOLVED MATTER IN WATERS COLLECTED IN BANCROFT AND ELLIOT LAKE

TABLE 23 AMOUNT OF TOTAL AND DISSOLVED MATTER IN WATER SAMPLES

		Spring Samples		Autumn Samples	
Location	No. of Samples	Total Matter[a]	Dissolved Matter[a]	Total Matter[a]	Dissolved Matter[a]
Elliot Lake	3	0.58 ± 0.32	0.59 ± 0.30	0.93 ± 0.54	0.93 ± 0.54
Bancroft	3	0.41 ± 0.25	0.25 ± 0.26	0.33 ± 0.47	0.35 ± 0.44
Seepages and Treatments	7	0.90 ± 0.78	0.73 ± 0.41	1.74 ± 0.60	1.72 ± 0.66
Controls: Elliot Lake & Bancroft	4	0.19 ± 0.70	0.10 ± 0.09	0.08 ± 0.10	0.10 ± 0.14

[a] measurements in g/L

Total and dissolved matter are differentiated based on filtration through 0.45 µm filters. For practical purposes, the concentrations of total and dissolved matter in the water associated with tailings can be considered more or less identical. The concentrations of matter determined in control samples give an indication of the increase in both matters in the water associated with the tailings. The fraction of particles which are retained on the filter paper appears to be relatively small (Table 24). Filter papers from the filtered samples were dried and weighed. The mean weight of the unused dried filters was subtracted from the mean weight of the used filters. The suspended particulate matter can thus be estimated to be around 0.055 g.

3.4.4 Heavy Metals and Radionuclides in Water on Tailings. The concentrations of copper, nickel, cobalt and lead in the tailings material (Section 3.2.1) indicated that given the acidic conditions of most tailings ponds, concentrations in the surface waters could reach significant proportions. However, not all the water collected had detectable metal concentrations. The percentage of samples which had detectable metal concentrations are compared for both areas (Figure 25). In Bancroft, 45% of all water samples had metal concentrations above the detection limit. The control water in this area was below the detection limit for cobalt, copper and lead while nickel was present in 15% of the Bancroft samples.

In the Elliot Lake area, nearly all of the water associated with tailings had detectable metal concentrations. Here, the percentage of detectable concentrations for

TABLE 24 SUSPENDED MATTER ON 0.45 μm FILTERS

	Unused Filters	Unused Filters (dried)	Filters with Suspended Matter
n	10	10	18
$\bar{x}$ (g)	0.0722	0.0695	0.1235
sd (g)	± 0.0021	± 0.0021	± 0.055

Legend: n = number of samples
$\bar{x}$ = mean
sd = standard deviation

nickel and copper in control water samples were around 50%, while cobalt and lead were detected in less than 20% of the samples. On the average, 40% of all the treated water samples had metal concentrations above the detection limit. The detection limits for atomic absorption analysis of copper, nickel, cobalt and lead in water are given in Appendix I.

The metal concentrations are presented for both areas as mean concentrations grouped in the categories discussed earlier (Figure 26). The concentrations in the control water for both areas are in the same ranges as those for the treated water of Elliot Lake. The metal concentrations differ somewhat between water on tailings and seepages. The concentrations of cobalt, nickel and copper are clearly higher in seepages than in the water on the tailings (two open bars in Figure 26). Note that a logarithmic scale of the metal concentration axis was needed to facilitate a comparison of metal concentrations in all of the water samples. For both water groups, the concentrations of cobalt, nickel and copper in the Bancroft water are clearly lower than in the Elliot Lake water. The concentration ranges found in water on tailings in both areas and in both water types are similar for lead. Seepages could not be differentiated from the water on tailings with this element.

The concentrations of radium-226 in water were also determined (Table 25). The mean concentrations of radium-226 vary and are presented for water on tailings and seepages for both areas separately. In Elliot Lake, the standard deviation is larger than the mean value of 18 pCi/L with a range of 1 to 72 pCi/L. The control and treatment water concentrations of radium-226 are low in both areas. The low values are often associated with large analytical errors.

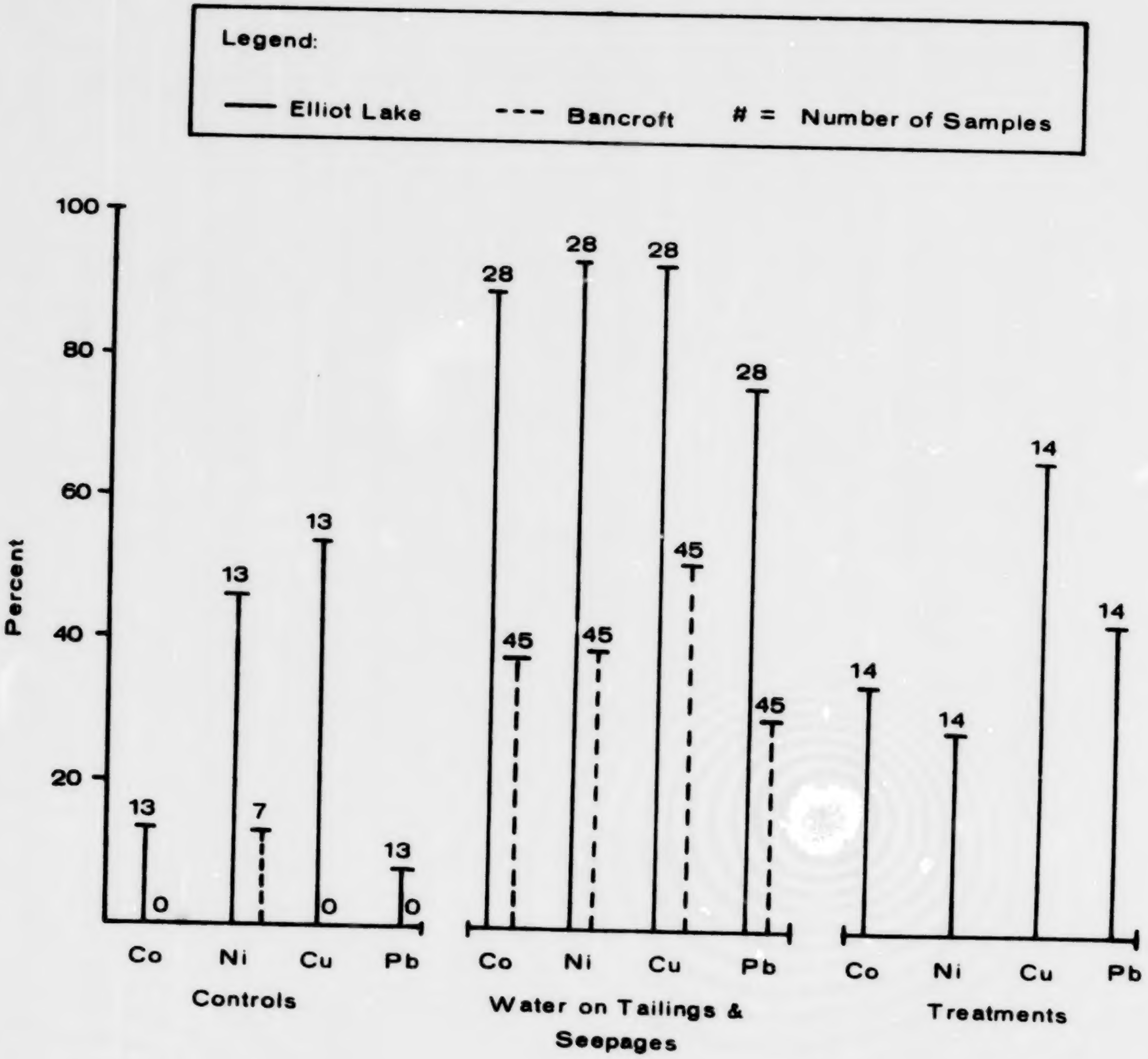


FIGURE 25 PERCENTAGE OF SAMPLES WITH METAL CONCENTRATION IN WATER ABOVE THE DETECTION LIMIT

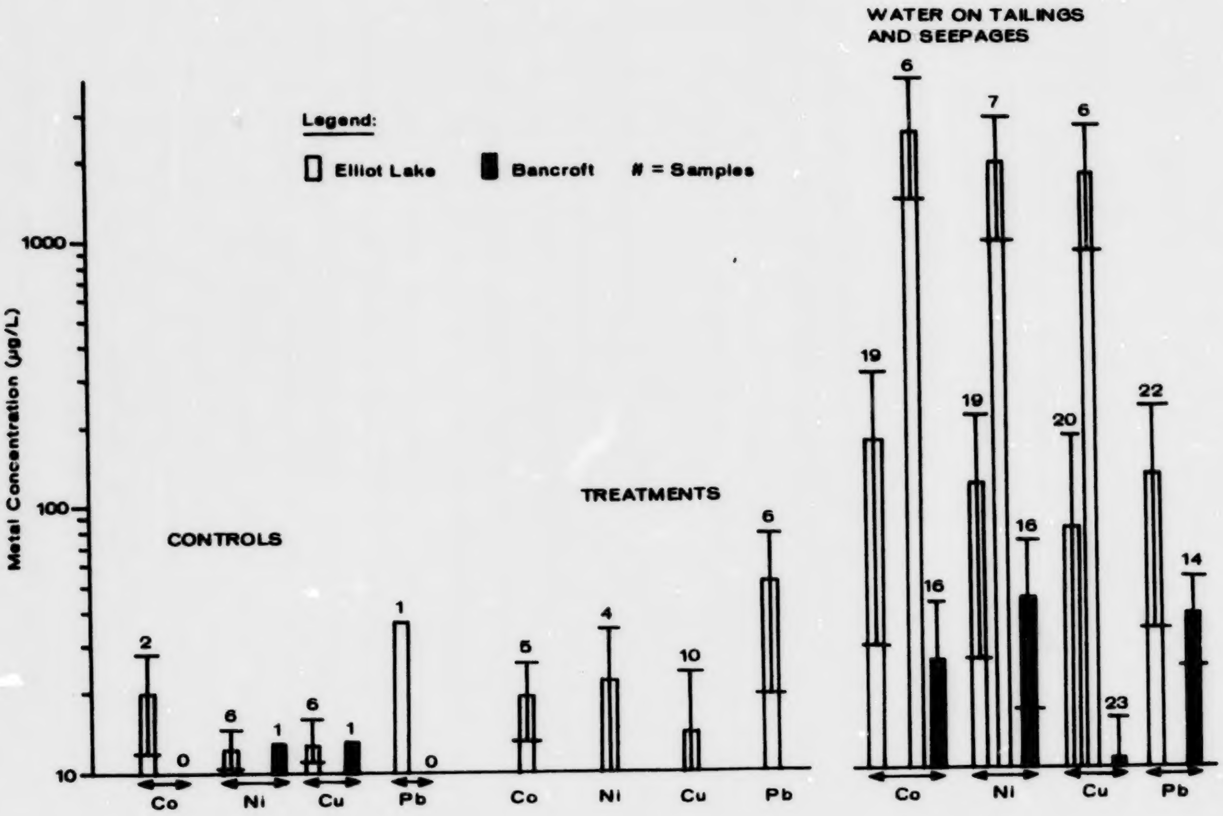


FIGURE 26 METAL CONCENTRATIONS IN GROUPS OF WATER

The radium-226 concentrations in water on tailings do not differ between Bancroft and Elliot Lake. The solubility of this radionuclide appears to be less related to the pH of the water than is the solubility of the metals. The radium-226 concentrations determined in surface water on tailings are relatively low, particularly when the total concentrations in tailings material are considered.

TABLE 25 MEAN RADIUM-226 CONCENTRATIONS IN WATER FOR THE BANCROFT AND ELLIOT LAKE AREAS

		Bancroft	Elliot Lake
Water on Tailings and seepages:	n	30	28
	$\bar{x}$	13	18
	sd	± 10	± 21
	max.	1	1
	min.	33	72
Controls and Treatments:	n	8	27
	$\bar{x}$	(4)	(2.5)
	sd	± 5	± 2
	max.	1	1
	min.	17	3

Legend: $\bar{x}$ = mean (pCi/L)
sd = standard deviation (pCi/L)
n = number of samples

Note: Analytical error can be as high as ±3 pCi/L to 0.5 pCi/L
Numbers in brackets are associated with large errors.

4 DISCUSSION AND CONCLUSIONS

One of the main objectives of the survey was the description and evaluation of abandoned or inactive uranium mill tailings sites to gain an indication of long-term environmental trends. The discussion therefore addresses the results of the survey with these objectives in view. Many aspects of the abandoned tailings sites are delineated only briefly and require more detailed analyses than were possible within the framework of this survey.

Approximately 35 million tonnes of 20-year-old tailings are investigated in this survey; this is but a small fraction of the expected Canadian tonnage of tailings by the middle of the next century. It can be argued that presently used waste management practices have improved compared to those used in the mid-fifties; consequently, the abandoned or inactive tailings sites may not reflect long-term environmental processes applicable to the future deposition of the waste material. On the other hand, the studied tailings sites can be considered as different experiments of tailings deposition.

The results are discussed in the following framework. The surface features and characteristics of the tailings ponds presented in Sections 3.1 and 3.2 are evidence that the time period of 15-23 years since the deposition of the tailings is sufficient to permit observations of ecological processes that occurred on the tailings ponds. The results suggest that variations in vegetation covers between and within the tailings sites can be studied and related to the physical and chemical characteristics of the tailings. Movements of elements from tailings to biota and water as presented in Sections 3.3 and 3.4 reflect some environmental effects of the tailings. Implications are apparent for management practices. Chemical data can be utilized in pathway models for hazardous elements from the tailings to the terrestrial and aquatic environments. Finally, the results of the survey provide a new perspective on the environmental effects of uranium mill tailings by generating comparative data.

Generally, tailings have been deposited mostly in natural depressions, a practice which is still prevalent (Table 1). More than half of the studied sites have received some form of amendments (Table 2). On some tailings sites, the process of amelioration was initiated 10 years ago. Vegetation covers have been established using a variety of seeded species under various amendment schemes with continued maintenance (Table 3). Revegetation of the tailings sites is presently considered an integral part of tailings management; extensive efforts have been expended in this area (Table 4). The maps of the tailings sites reflect the success of the revegetation programs. However, the long-term stability of the established vegetation cover is not known. The presence of naturally colonizing vegetation allows the investigation of the process of invasion of the tailings by indigenous species. On naturally disturbed sites, the first 10-30 years are generally dominated by primary colonizing species. The composition of common and frequently identified species on the tailings sites suggests that primary colonization is presently taking place (Table 6). *Populus tremuloides* and *Betula papyrifera* are considered primary colonists on disturbed lands in northern deciduous woodlands (Grime, 1979). Other species of vascular plants identified on dry areas of the tailings ponds are species typical of wastelands and road sides (Table 7).

The classical view of ecological succession predicts that older wasteland sites are colonized by a larger number of natural species. Such a relationship was not apparent on acidic colliery spoils (Bradshaw and Chadwick, 1980). The observations presented in Table 8 similarly do not suggest any relationship to the age, but possibly to the type of amendment. The lists of species compiled during this survey provided only qualitative information. Quantitative investigations are necessary in order to determine plant succession on the waste sites. Many of the tailings sites were shown to have mixtures of indigenous and seeded species (Figure 3).

The wet areas of the tailings ponds are inhabited exclusively by indigenous vegetation. The repeated occurrence of members of the families Cyperaceae, Typhaceae and Juncaceae on tailings sites is illustrated in Tables 6 and 7. This wetland vegetation group is of particular interest to the tailings areas. Sizeable wetland stands have been documented on these types of sites (Maps 5, 6 and 16). The importance of this vegetation type is further emphasized by observations of pH changes in the root region (Figures 8 and 9) and of the acid tolerance (McNaughton et al., 1974; Hargreaves et al., 1975) of the dominant species *Typha* (cattails). The tailings sites which are completely overgrown by wetland vegetation generate interest in investigating the potential of this vegetation in the mitigation of the tailings environment.

Vegetation types which may be useful in the identification of long-term trends have been discussed; however, the information on the maps reflects also a tremendous heterogeneity of the surface. Knowledge of the characteristics of the growth-supporting material may assist in clarifying the causes of the observed heterogeneity. However, chemical and physical characteristics of abandoned tailings are variable. The elemental concentrations in tailings deviate from those found in soils (Table 13); however, for the most part variations encountered in the tailings are similar to those in soils (Table 12). Some elements are enriched while others are somewhat depleted (Table 9) in comparison to values reported for soils. On some inactive tailings sites, elevated concentrations of heavy metals can be encountered locally, but they never occur consistently throughout a site (Tables 10 and 11). A possible approach to evaluating the ranges of elements in tailings compared to soils is shown in Table 13. It may be possible to overcome the problem of the "representative" tailings sample by considering elemental concentration ranges.

For other parameters, the variations are too large, such that the ranges differentiate tailings from soils clearly. The characteristics of pH, conductivity, organic matter and moisture content exhibit enormous differences between tailings materials and soils (Tables 13, 14 and 15). These differences are of significance to the long-term development of biota on the tailings as are differences in elemental enrichment or depletion. The existing vegetation covers on the tailings sites are in part the results of man's efforts as well as a reflection of the tolerances and adaptations of vegetation to disturbed lands. Some deficiencies of tailings are overcome in the short-term by additions of stabilizing materials and fertilizers. The future of the tailings areas will be mainly reflected in the ability of indigenous and introduced vegetation to respond to the environment of the tailings. In 10-20 years (the age of the tailings), no substantial developments of soil can be expected. Bradshaw and Chadwick (1980) cited a period of 40 to 100 years as the time frame for the development of a soil structure on naturally disturbed lands. The nutrient status, differences between tailings and soil, and the elemental deficiencies or enrichments have not, however, prohibited growth of certain indigenous species. Nevertheless, all natural plant communities experience some stresses and may specialize to adapt to these stresses. Tolerances in indigenous plants to the conditions of the tailings are suggested by some observations of the root region (Figures 8 and 9). Plants control the chemical environment in the rhizosphere (Harley and Russell, 1979). The pH trend of the root regions for the wetland vegetation is reversed compared to those of the trees (Figures 8 and 9). The rehabilitation in the long-term is dependant upon the success of primary colonists to sustain the stresses of the environment on the tailings.

The uptake of long-lived radionuclides and heavy metals by indigenous vegetation may facilitate the transfer of these elements to the environment. This could result in undesirable effects and ultimately in the contamination of the food chain.

Fundamental to an evaluation of environmental effects of tailings is, therefore, the movement of hazardous materials from the tailings to biota and the surroundings. A preliminary appraisal of heavy metals and radionuclides in indigenous vegetation is given in this survey.

The preliminary results indicate that metals are present in all tree organs. The concentration ranges are close to those normally encountered in land plants (Bowen, 1966). White birch appears to have higher metal concentrations than does trembling aspen suggesting a species difference in the uptake behaviour. In general, the metal uptake in trees is low and cannot be related to the tailings material. In *Typha*, the metals are retained in the roots; less than 50% of the metal concentration is found in the aerial parts of the mature plants (Table 20).

The distribution patterns of metals within the trees and *Typha* are important. The uptake follows the expected behaviour for essential and non-essential elements in both types of plants (Timperley et al., 1970). In *Typha*, the elements are not available to the consumers (animals) whereas in trees they are transported to the aerial parts. Thus, the fate of metals must be evaluated in the root region of wetland stands. The fate of metals in trees, however, may be of more interest in the long-term with respect to the age of the trees.

Radium-226 and lead-210 in trees and *Typha* exhibit trends in uptake similar to those of the metals discussed above. The radium concentrations in all tree organs were, however, somewhat higher in the Bancroft area than those in the Elliot Lake area. Further evaluation of uptake in trees of radionuclides awaits the analyses of the tailings associated with the collected trees. Future studies to delineate radium-226 uptake in white birch are of particular interest since the concentrations determined in individuals of this species were high (Table 21).

The uptake of radium-226 and lead-210 by *Typha latifolia* was discussed in detail by Kalin and Sharma (1981a). Both radionuclides appear to be excluded by *Typha*, as opposed to being accumulated (Figures 15, 16 and 17). The availability of radium-226 to plants in soils may differ from that in the tailings. The transport of radium-226 to biota and water is likely governed by the physico-chemical forms of the element (Benes, 1981). The forms of radium-226 are likely to differ in the tailings and the soils. As the transport of radium-226 from the tailings to biota of the terrestrial, aquatic and the semi-aquatic habitat is related on the solubility of the element, the forms of radium-226 require intensive study. Controlling factors of radionuclide movement from the tailings to biota are still unclear. The effects of these elements in the root region of the plants and the concentrations in litter which accumulates on the surface are unknown.

The water on abandoned tailings sites is also described in this survey. Several of the investigated sites were either completely covered with water, or had large portions of the deposited tailings under water. The tailings ponds of the future may be drier than these sites; however, some water will always be present. The survey described ecologically significant parameters of the surface water and some aspects of its seasonal behaviour.

The acidic effluents from the inactive tailings are neutralized and radium-226 is removed. This process has been shown to affect the characteristics of the surface water. Abandoned tailings water is not treated; in the long-run, the treatment operation on the inactive tailings will cease. The characteristics of the aquatic ecosystem, which will undergo changes due to the ultimate cessation of the treatment, have to be known to evaluate the behaviour in the long-term. Thus, an overall assessment of tailings surface water has also to include the characteristics of treated surface water. A detailed discussion of characteristics of the aquatic ecosystem is in preparation.

The pH and conductivity of water, and the productivity of algae in the surface water differed from the controls for all tailings water types investigated (Figures 18, 19 and 20). The water on tailings and from the seepages were acidic, but generally the pH was not much lower than that of naturally acidic environments such as acid bogs. The productivity as measured by chlorophyll *a* is only an approximation of algal biomass. In the water on tailings, chlorophyll *a* values were in the same range as determined for oligotrophic environments (EPA, 1973). However, a drastic reduction of chlorophyll *a* was observed in treated waters.

In general, most characteristics of the water on the tailings followed predictable relationships (Figures 22, 23 and 24). Metal concentrations were found to be higher in the seepages than in the water on the tailings ponds. In a large number of the water samples, metal concentrations were, however, surprisingly low considering the acidic nature of the water (Figure 26).

Radium-226 concentrations were extremely variable in all water body types on the tailings. A relationship between dissolved fractions of radium-226 and those of magnesium and calcium in surface water on tailings has been described by Kalin and Sharma (1981b). The availability of water soluble group two elements in the tailings may explain some of the observed variations in radium-226 concentrations.

Despite acidic waters, the metal and radionuclide concentrations, and the high conductivity of the water some encouraging observations await detailed attention. Aquatic bryophytes have invaded the water on tailings and algal blooms were observed in some of the water bodies. Extensive wetland communities have developed on some of the water covered tailings sites. It can be speculated that a natural amelioration may be possible in the long-term by the development of these biological systems. Biological means of fixing dissolved elements in water on tailings are possible alternatives to the chemical treatments of the water. In conclusion, it is emphasized that ecological processes which occur on the inactive tailings sites reveal an abundance of means to evaluate the long-term fate of these waste materials.

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APPENDIX I

DETAILED METHODS

APPENDIX I DETAILED METHODS

Washing and Grinding of *Typha* and Trees

The stems, leaves and fruits were separated and rinsed with tap water. A second wash was carried out with detergent (Palmolive brand) and was followed by three rinses in distilled water. The plant parts were frozen to prevent any decay while awaiting further preparation. The parts were subsequently cut into small pieces and homogenized in a blender (Waring Commercial) often with the addition of some distilled water. The amount of water added depended upon the material. All the samples were dried at a temperature of 78 to 85°C.

Roots and rhizomes were scrubbed with a brush and inspected microscopically for remaining attached tailings material. When the parts were considered clean, they were rinsed in the detergent water followed by three rinses of distilled water. The material was then homogenized in the blender in the same way as all other plant materials.

The blender container was rinsed with diluted HCl between each sample to prevent cross contamination. The washing procedures were carried out with gloves.

Chlorophyll *a* Determination

Reagents - as in ASTM Book of Standards (see text for D 3731-79)

Material and Apparatus specification:

- Gelman 0.45 μm membrane filters
- Whatman 2.4 cm (934 AH) glass fibre filters
- filter fluorometer with filters equivalent to those listed in ASTM Book of Standards
- International Clinical centrifuge (No. 221 Head)
- 15 mL glass centrifuge tube
- Spectrophotometer (Beckman)

Extraction: The only deviations from ASTM procedures are given below:

- Membrane filter with harvest were dissolved in 3 mL of 90% aqueous acetone to which half of a 2.4-cm glass fibre filter (shredded) was added.
- Following homogenization (for 5 minutes not 3 minutes) the extraction was brought to 5 mL (not 10 mL) to facilitate a measurement of low values. To minimize dilution of extract with any water on the filter (to maintain 90% in

extract), any filters which appeared wet were placed on filter apparatus briefly at reduced pressure.

Analysis: (as per ASTM)

The standard used to calibrate the fluorometric readings was an extract of a *Scenedesmus* species, analyzed by spectrophotometry using the listed wavelengths. When not being analyzed or centrifuged, all materials (harvests, homogenates, extracts, supernatants) were kept in an ice bath shielded from the light. No attempt was made to correct for pheophytin a.

Atomic Absorption Spectrophotometry

Spectral lines used were: Cu, 324.7 nm; Ni, 232.0 nm; Co, 240.7 nm; and Pb, 217.0 nm and 283.3 nm. For the metal lead some comments are warranted. Despite the associated poor sensitivity of the 283.3 nm line of Pb, this line was used for several analytical runs, in which substantial background values were detected. In these samples, regardless of which line was used, the background values were frequently significant.

Background: Background or non-atomic absorbance was measured in all analyses by means of a Varian H_2 lamp.

Standards:

Water: The standard matrix was glass-distilled water, acidified to ~0.7% (by weight) nitric acid (Baker and analyzed).

Plant digests: The standards were made up in a 50% nitric acid matrix (i.e. 50 mL of concentrated HNO_3 per 100 mL). HNO_3 used to prepare the standard was Anachemia reagent grade for Cu, Ni and Pb analyses, and Baker analyzed HNO_3 in the case of the Co standard. The analytical blank represented the above matrix.

Tailings or soil: The blank and standard matrices consisted of 10 mL HNO_3 (conc.) and 10 mL $HClO_4$ (conc.) per 100 mL. The acids were of the same grade as in the plant digest for each respective element measured.

Dilutions: Any necessary sample dilutions were performed with either volumetric pipettes, flasks or with automatic "pipetman" pipettes in the respective matrix.

Recordings: All analyses were recorded on a Nesco strip chart recorder.

SUMMARY OF EPA WATER VALUES (all values in μg/mL)

Our determinations	Cu	Ni	Co	Pb
EPA No. 2	0.41	0.16	0.34	0.39
(476E)	0.40	0.15	0.35	0.41
determined	0.41	0.17	0.35	
	0.41	0.19	0.35	
		0.18	0.36	
			0.34	
Mean	0.40	0.17	0.35	0.40
Standard deviation	± 0.004	± 0.015	± 0.005	
Expected concentration	0.374 ppm	0.165 ppm	0.384 ppm	0.383 ppm

ATOMIC ABSORPTION DETECTION LIMITS AND ERRORS

Element	Water	Plants		Soil/tailings	
(a) Detection limits (mg/L or μg/g dry weight)					
Cu	0.003	0.12	(0.5)	0.25	(1.0)
Ni	0.008	0.2	(0.8)	0.4	(1.5)
Co	0.007	0.2	(0.8)	0.4	(1.5)
Pb	0.020	0.5	(2.0)	1.0	(4.0)
(b) Errors estimated (± mg/L or ± μg/g dry weight)					
Cu	0.006	0.08	(1.25)	0.2	(2.5)
Ni	0.006	0.16	(1.6)	0.3	(3.0)
Co	0.006	0.16	(1.6)	0.3	(3.0)
Pb	0.006	0.3	(3.0)	1.8	(18.0)

The values in parentheses represent the errors for those few samples with relatively small sample weight (approximately 0.200 g). Estimates are based in 0.5 mm deflection, which may be the largest contribution to the error. Source: EPS-5-WNR 81-1 (Kalin, M.)

CONTROL OF ANALYSIS AND DIGESTION PROCEDURE

Nature of Samples		Cu	Ni	Pb	Co
		μg/g			
Standard sediment	our analysis	740	33.8	2980	4.3
sludge C.C.I.W.	listed values	776 ± 67	32.7 ± 3.6	3100 ± 200	not given
Orchard leaves	our analysis	11.4	0.58	47.3	0.2
NBS No. 1571	listed values	12 ± 1	1.3 ± 1.2	45 ± 3	0.2 not certified

Note: Water values are given for EPA water in Table 26.

Source: EPS-5-WNR 81-1 (Kalin, M.)

Neutron Activation Analysis (by J. Blondal)

Theoretical Considerations. The sample to be analyzed is irradiated with a fixed known flux (ϕ) of thermal neutrons for a specific time (t_{irr}). An element amenable to activation analysis must, in this process, produce an unstable isotope in sufficient yeild to allow detection of its γ ray emissions. All the isotopes pertinent to the present discussion result from (n, γ) reactions, e.g. ^{27}Al (n, γ) ^{28}Al (i.e. $^{27}_{13}\mathrm{Al} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{28}_{13}\mathrm{Al} + \gamma$). In the above example, ^{28}Al then decays via β^- decay with an accompanying emission of a γ ray of energy 1779 keV.

Allowing for a decay time of Δt, the activity $A_{\Delta t}$, of the induced radioactive isotope produced from N atoms of the element in the sample is:

$$A\ \Delta t = N\ \phi\sigma\left(1 - \exp(-\lambda\ t_{irr})\right)\exp(-\lambda\ \Delta t),$$

where: σ is the nuclear reaction cross-section and $\lambda = \ell n\ 2/T\ 1/2$ is the decay constant for the radioactive isotope.

Practical Considerations. The technique employed involved no chemical separation or treatment and is therefore entirely instrumental. A sample is placed in a 1-mL polyethylene vial and is irradiated according to one of the following irradiation schemes described in the following table. Water samples are transferred to a fresh vial immediately after irradiation.

Sample Type	Irradiation Time (min)	Reactor Power (kW)	Decay Time (min)
water	6	20	2
soil/tailings	1	2	15 - 20
vegetation	1	10	5 - 15
acid digestions	6	10	10

Following irradiation, the samples were counted for 5 minutes on one of the two X-ray spectrometers. The 4096 channel memory was used. The final print-out yields integrated counts of selected peaks and their adjacent backgrounds of the activated samples γ energy spectrum. Sample-to-dectector distance (that is sample position) is increased for those samples whose associated dead-time would otherwise be significant (> 15-20%).

In practice, the samples' activity is compared to that of a set of standards prepared for each element. Use of such a direct comparison is based on the assumption that the isotopic abundances in both samples and standard are identical for a given chemical element. This is valid for all elements analyzed here.

For a given irradiation scheme (irradiation time t_{irr} and power Z) and decay time Δt, the specific activity F_o (counts rather than decays) is found for a given isotopic standard from the expression:

$$F_o = (P - B)/(\exp(-\lambda \times \Delta t) \times \mu g \text{ element irradiated})$$

in counts per µg per five (5) minutes. Here the expression has been back-extrapolated to $\Delta t = 0$, and P and B are the integrated peak and background counts, respectively.

For those samples irradiated at Z' kW for t'_{irr} and counted at a position "p", a new F_o' corresponding to these conditions can be calculated for each element as follows:

$$F_o' = F_o \times \frac{Z'}{Z} \times \frac{1 - \exp(-\lambda \times t'_{irr})}{1 - \exp(-\lambda \times t_{irr})} \times C_p$$

where C_p is a correction factor determined experimentally by counting an irradiated standard at position "p".

An elemental concentration in a given sample can then be calculated in units of µg/g as:

$$(P - B)/(\exp(-\lambda \times \Delta t) \times Wt \times F_o)$$

where Wt is the samples weight in grams, Δt is the decay time, P and B are the measured peak and background counts for the appropriate γ ray, and F_o is chosen for the appropriate operating parameters t_{irr}, Z, counting position, and counter.

Errors. A major source of experimental error is derived from the statistics of counting, here: $\sigma = \sqrt{P + B}$. Thus, for a significant net peak (P - B) the error (as a percentage) is given by:

$$\left(\frac{\sqrt{P + B}}{P - B}\right) \times 100\%$$

The approach used in checking whether the counts are significant is as follows: if $P - B > 4.65\sqrt{B}$, then the peak is significant. Otherwise, there is no "real" peak, and an approximate detection limit can be obtained by using $4.65\sqrt{B}$ rather than P - B in the ensuing calculations.

For one of the two counters used, an anomalous net background count was found at the γ ray energy (74.6 keV) corresponding to the ^{239}U isotope used in measuring uranium content. This peak was counted for each analytical run and was subtracted from the sample counts at that γ ray energy. In addition, a correction was made for the contribution of the reaction ^{28}Al (n, p) ^{27}Mg to the ^{27}Mg peak used for magnesium determinations.

A Calculated Example. Suppose a 0.5438-g sample was irradiated at 10 kW for 6 minutes and counted on counter No. 1 at position 4 after Δt = 15 minutes. The F_o of the 1811 keV peak of ^{56}Mn ($\lambda = 0.00447\ \text{min}^{-1}$) is 28.8 for an irradiation of 1 minute at 2 kW reactor power. The pertinent F_o' is then:

$$F_o' = 28.8 \times \frac{10\ \text{kW}}{2\ \text{kW}} \times \frac{1 - \exp(-0.00447 \times 6)}{1 - \exp(-0.00447 \times 1)} \times 0.450 = 384$$

where C_p - 0.450 is the correction factor for the ^{56}Mn 1811 keV peak for position "4".

Peak and background counts for that peak were 2800 and 57 respectively. The concentration of manganese in the sample was then:

$$(2800 - 57)/(\exp(-0.0047 \times 15) \times 384.5 \times 0.5438) = 14.0\ \mu g/g$$

The error associated with counting statistics was:

$$\pm \quad \frac{\sqrt{2800 + 57}}{2800 - 57} \times 14.0\ \mu g/g$$

that is ± 0.3 μg/g, therefore the concentration of Mn in the sample is 14.0 ± 0.3 g/g.

The F_o for 1 min at 2 kW and a counting position 1 used for the calculations are given in the following table.

F_o FOR 1 Min AT 2 kW COUNTS AT POSITION 1

Element	λ (min^{-1})	F_o Counter 1	(Cl) P4/P1	F_o Counter 2	(C2) P4/P1
Co	0.066	504	0.379	472	0.525
U	0.0294	1700	0.384	2290	0.527
Dy	0.00495	3870	0.383	5220	0.525
Ba	0.00835	4.83	0.382	9.09	0.520
Ti			0.386		
Sr	0.00407	1.57	0.388	2.99	0.507
I	0.0276	110	0.390	235	0.547
Br	0.0393	44.1	0.395	89.7	0.506
Mg	0.0732	0.401	0.420	0.799	0.525
Na	0.00077	1.70	0.437	3.25	0.540
V	0.184	1110	0.443	2010	0.534
Al	0.3000	83.7	0.443	169	0.525
Mn	0.00447	28.8	0.450	51.8	0.533
Cl	0.0185	1.47	0.450	2.78	0.525
Ca	0.0787	0.129	0.450	0.241	0.574

Correction Factor for P8/P1 0.102 and P10/P1 0.045.

R. Hancock F_o: Dy 1550 (our results 50% lower)
Mn 20.5 (our results 30% lower)
Cl = Counter 1
C2 = Counter 2

(Standards run in Dec. & Jan. 1980; J. Blondal)

STANDARD MATERIAL ANALYZED BY NEUTRON ACTIVATION ANALYSIS DURING SAMPLE DETERMINATIONS

		Co	U	Mg	Na	V	Al	Mn	Ca
		μg/g							
N.B.S. Coal No. 1631	our* analysis	5.6 ±0.6	1.66 ±0.12	1 800 ±180	403 ±36	34.3 ±1.4	17 100 ±170	41.0 ±2	2 630 ±290
	given	5.7 (±0.4)	1.4 (±0.1)	2 000 (±500)	414 (±20)	35.0 (±3)	18 500 (±1 300)	40.0 (±3)	4 300 (±500)
Orchard leaves SRM No. 1571	our* analysis	0.9[a]	0.2[a]	6 220 ±200	58 ±28	0.55 ±0.17	419 ±11	96.8 ±2	13 450 ±400
	given	0.2 not certified	0.029 (±0.005)	6 200 (±200)	82 (±6)	not given	not given	91.0 (±4)	20 900 (±300)

* Errors are calculated as $(\sqrt{P + B}/P - B)\ 100$

( ) = standard deviation

[a] detection limits

Source: EPS-5-WNR-81-1 (Kalin, M.)

Detection Limits and Errors in Neutron Activation Analysis

TYPICAL RANGES OF DETECTION LIMITS IN MATERIALS OF THIS SURVEY

Elements	Water (mg/L)	Soil/tailings (μg/g)	Vegetation (μg/g)
Al	0.06 - 0.4	*	*
Ba	0.4 - 1.0	*	10 - 65
Br	0.01 - 1.5	10 - 70	2 - 10
Ca	2 - 7	300 - 1000	*
Cl	1 - 5	*	*
Dy	0.001 - 0.04	0.2 - 0.8	0.05 - 0.5
I	0.002 - 0.01	1 - 20	1 - 10
Na	*	*	24 - 70
Mg	2 - 20	*	300 - 500
Mn	0.02 - 0.5	*	*
Sr	0.5 - 1.5	150 - 600	64 - 150
U	0.002 - 0.05	*	0.1 - 0.3
V	0.002 - 0.015	*	

The ranges given are based on the materials analyzed in this survey. They do not reflect detection limits and errors of neutron activation analysis in general. The asterisks (*) indicates those instances where sample concentrations are well above detection limits for all samples analyzed. The figures given are typical values; however, isolated samples exist where the values will be considerably lower or higher.

TYPICAL RANGES OF ERRORS (IN PERCENT) ASSOCIATED WITH THE DETERMINATIONS IN THE MATERIAL

Element	Water (mg/L)	Soil/tailings (μg/g)	Vegetation (μg/g)
Al	0.1 - 10	1 - 2	1 - 5
Ba	10 - 25	1 - 15	5 - 15
Br	2 - 20	15 - 30	5 - 20
Ca	3 - 30	1 - 20	1 - 8
Cl	1 - 20	2 - 30	2 - 28
Dy	2 - 25	1 - 10	5 - 25
I	7 - 30	10 - 25	10 - 20
Na	0.3 - 13	0.6 - 1	5 - 15
Mg	1 - 30	2 - 10	3 - 14
Mn	1 - 5	0.5 - 5	2 - 5
Sr	N/A	17 - 30	N/A
U	0.3 - 10	0.4 - 16	3 - 20
V	1 - 10	1 - 10	5 - 20

N/A = not applicable

Radiochemistry for Radium-226 and Lead-210 Determinations (by H.D. Sharma)

Preparation of Materials. Radium adsorbs onto active sites in untreated glassware, resulting in effective radium loss. To prevent this, all glassware was coated with a silicon solution and then baked at high temperatures overnight to provide a firm coating.

Preparation of Cation Exchange Resin. Dowex 50W-X8 (200 - 400 mesh) resin in the H^-cation form was used. The resin was conditioned by allowing it to stand for 48 hours in a 3 N HCl solution. It was then de-aerated and 5.0 to 9.0 cm^3 of the resin was filled into a column (10 x 2 cm). The packed column was washed with de-ionized distilled water.

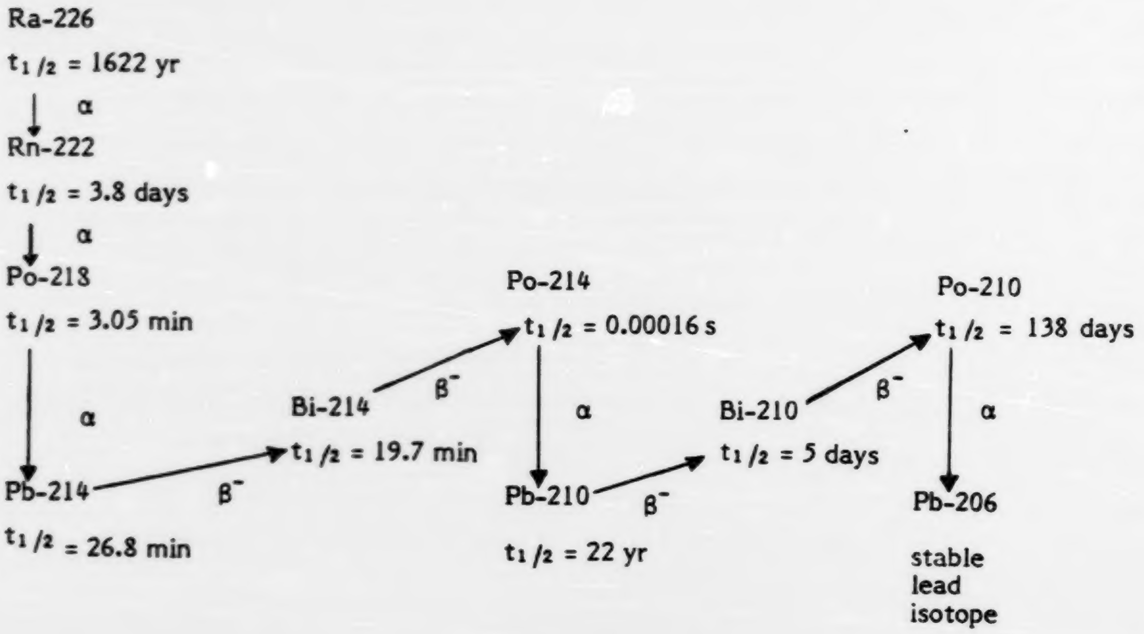
Sample Preparation. The samples were prepared at the Institute for Environmental Studies and supplied either as a solid or as a liquid sample. The liquid samples (water and vegetation digest) were adjusted to a pH range of 1.0 to 2.5. The solid samples (tailings and soils) were dried and each sample was placed in a Nalgene bottle with 30 mL of DTPA (Diethylenetriaminepentacetic acid). DTPA acts as an extracting agent bringing radium sulphate and other cations into the solution. The solution was centrifuged and acidified with HCl to pH 1-2.

Radioanalysis. The solution was passed through the cation exchange resin. The absorbed radium was eluted by passing 200 mL of 12 M HCl through the column. Six M HCl forms a constant boiling azeotrope, thus it can be prepared by boiling 12 M HCl down to approximately half volume. The resulting 6 M HCl solution was diluted to 3 M with distilled water and placed in a 125 mL Nalgene bottle.

Because of the sub-picogram yields of nuclear decay products, 1.0 μg of lead and 1.0 μg of bismuth inert carriers were added to the sample. Isotopic exchange between inactive and the radioactive isotopes was ensured. Further, 0.7 mL of a 2% solution of hydrazine dihydrochloride was added to ensure that the oxidation states of lead and bismuth were (II) and (III) respectively. Finally, a few drops of xylene were added to provide a covering for the solution to prevent escape of any radon gas.

The solution of the sample thus prepared was stored for a minimum of 3.8 days (the half-life of Rn = 3.8 days) to allow the growth of the daughter products.

The decay of radium-226 occurred to its daughter products during storage as shown in the following figure. The accuracy of the method depends on ensuring that no radon gas escapes during the storage period.


Ra-226
$t_{1/2}$ = 1622 yr
α
Rn-222
$t_{1/2}$ = 3.8 days
α
Po-218
$t_{1/2}$ = 3.05 min
α
Pb-214
$t_{1/2}$ = 26.8 min
β⁻
Bi-214
$t_{1/2}$ = 19.7 min
β⁻
Po-214
$t_{1/2}$ = 0.00016 s
α
Pb-210
$t_{1/2}$ = 22 yr
β⁻
Bi-210
$t_{1/2}$ = 5 days
β⁻
Po-210
$t_{1/2}$ = 138 days
α
Pb-206
stable
lead
isotope

Lead and bismuth were extracted from the aqueous solution with 4.0 mL aliquots of DADDC (diethylammonium diethyldithiocarbamate) solution in xylene. This DADDC solution is prepared by mixing a solution of 5.0 mL of diethylamine in 45.0 mL of xylene with 10.0 mL of carbon disulphide in 40 mL of xylene. This procedure results in the extraction of the Pb-210, Pb-214, Bi-214 and Bi-210 into the organic layer. This organic layer is pipetted onto a stainless steel planchet and placed under a heat lamp. It is essential that the extraction is carried out within 20 minutes as the half-lives of Pb-214 and Bi-214 are short. The organic layer is evaporated, leaving lead and bismuth on the planchet.

The activities due to Bi-210, Bi-214 and Pb-214 were assayed with a gas flow proportional counter for beta activity for 1 hour subsequent to the extraction. The Pb-210 was not detected because of its low beta decay energy. The sample was counted again 1 day after the separation. The activities due to Bi-214 and Pb-214 had essentially decayed to negligible amount as their half-lives are 19.7 and 26.8 minutes respectively. By assuming that secular equilibrium exists between Pb-210 and Bi-210, the activity of Bi-210 is then equal to that of Pb-210. Thus the second assay minus background equals Pb-210 activity.

The assay results were then used by applying the standard decay equations for the determination of Ra-226 in the sample. An example of the calculation is given below:

Initial Pb-214 Activity

$$A_C = E_d \quad \frac{A_0 e^{-\lambda_1 t_e}(1 - e^{-\lambda_1 t_C})}{\lambda_1} + \frac{\lambda_2 A_0 \, e^{-\lambda_1 t_e}(1 - e^{\lambda_1 t_C})}{(\lambda_2 - \lambda_1)\,\lambda_1}$$

$$- \quad \frac{A_0 \, e^{-\lambda_2 t_e}(1 - e^{-\lambda_2 t_C})}{\lambda_2 - \lambda_1} + \frac{A_0 \, e^{-\lambda_2 t_e}(1 - e^{-\lambda_2 t_C})}{\lambda_2}$$

Where:

A_C - the number of counts due to Pb-214 and Bi-214 = (first count - background) - (second count - background)

A_0 - initial activity of Pb-214 (at the time of the start of the extraction)

t_e - time of duration of extraction in minutes

t_C - duration of the counting period = 60 minutes

λ_1 - ln $2/t_{1/2}$ in minutes for Pb-214

λ_2 - ln $2/t_{1/2}$ in minutes for Bi-214

E_d - calibrated efficiency of the detector

This equation reduces to:

A_c = Ed $A_0 f(t)$, where f(t) is calculated for various values of t_e:

t_e = 13 min, f(t) = 59.5176

t_e = 17 min, f(t) = 55.6632

t_e = 18 min, f(t) = 54.5862

t_e = 19 min, f(t) = 53.5253

t_e = 20 min, f(t) = 52.4517

The reduced equation is solved for A_0 and A_0 substituted into the equation A Ra-226 = $A_0/(1 - e^{-\lambda_3 t_s})$ where A Ra-226 = activity of radium-226 and λ_3 = ln $2/t_{1/2}$ in minutes of Rn-222 = 5472 min, t_s = storage time.

$$\text{A Pb-210} = \frac{\text{(number of second counts - background)}}{2.2 \times E_d \times 60}$$

Error:

$$\text{Ra-226:} \quad \text{Error:} \quad \frac{\text{(net number of counts (first and second) + ave. background)}^{1/2}}{60 \times 2.2 \times E_d \times \text{wt} \times \text{(in g or L)}}$$

$$\text{Pb-210:} \quad \text{Error:} \quad \frac{\text{(number of second counts + background)}^{1/2}}{60 \times 2.2 \times E_d \times \text{wt (in g or L)}}$$

Both results in ± pCi, 1 pCi = 1×10^{-12}Ci

Determination of radium standard activity. To determine the activity of the radium standard, alpha-ray spectroscopy was employed. A 0.2-mL sample of the standard was evaporated on a planchet. The planchet was placed in the alpha counter and counted overnight. The total number of counts under the appropriate peak were recorded.

$$\text{Activity} = \frac{\text{total counts x geometry factor}}{\text{counting time (min x 2.22 x 0.2 mL)}}$$

Geometry factors = 3.60

Using this procedure, the activity of the standard solution was determined. All analytical procedures were examined by using the standard solution.

APPENDIX II

BACKGROUND INFORMATION

APPENDIX II BACKGROUND INFORMATION

Estimates of Tailings Tonnage

Dyno. Griffith (1967) gives a production of yellow cake by the end of 1959 of 693 000 lbs. The ore grade is assumed to be on the average of 0.075%. Therefore, it is estimated that 0.42 million tonnes of tailings were produced. However, the mill operated until the end of the year 1960. Thus the production of tailings during the year of 1960 has to be added to arrive at the total amount of tailings produced.

The mill shutdown operations in June 1960. Therefore, for 6 months the mill can be expected to have operated at 1200 tonnes per day. At full operation the mill would have worked 6 x 30 days for a total of 180 days. If 75% operation time is assumed then 135 days will result in an additional tailings tonnage of 162 000 tonnes. The total tailings tonnage for Dyno is therefore 0.42 million tonnes from production 1959-1960 and 0.16 from the year of 1960 for a total of 0.58 million tonnes of tailings.

Panel Dam A. The tailings tonnage estimate of 0.24 million tonnes is based on a survey by Rio Algom Limited. It was estimated that 153 000 m^3 of tailings were present in the Panel Dam A area. The tailings tonnage calculated was based on the assumption that the tailings have a volume of 20 ft^3 per short ton (Vivyurka, 1980).

Surface Area of Stanrock Main. Several quotes of the surface area for ths site exist; these vary from 55 to 61 ha. After a discussion of our method used to obtain the surface area with Denison Mines Limited, an agreement was reached that the surface area of Stanrock Main is 63 ha (Blackmore, 1980).

Statistics Used in this Report

The following formulas were used in the calculation of the statistics:

Mean: $$\bar{X} = \frac{\Sigma X}{N}$$

Kurtosis $$= \frac{\Sigma_{i}^{N} = 1 \; ((X_i - X)/s)^4}{N} - 3$$

$$\text{Skewness} = \frac{\Sigma_{i}^{N} = 1 \quad \left[(X_i - \bar{X})/s\right]^3}{N}$$

$$\text{Standard deviation:} \quad sd = \left[\frac{\Sigma X^2 - \frac{(\Sigma X)^2}{N}}{N - 1} \right]^{1/2}$$